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Title: Anisotropic Reverse-Time Migration for Imaging Fracture Zones at Eleven-Mile Canyon

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Anisotropic Reverse-Time Migration for Imaging Fracture Zones at Eleven-Mile Canyon

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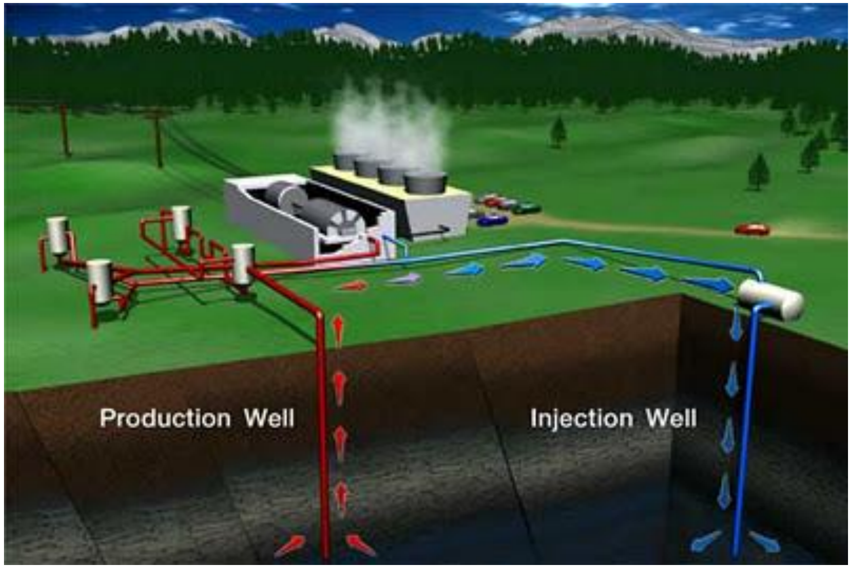
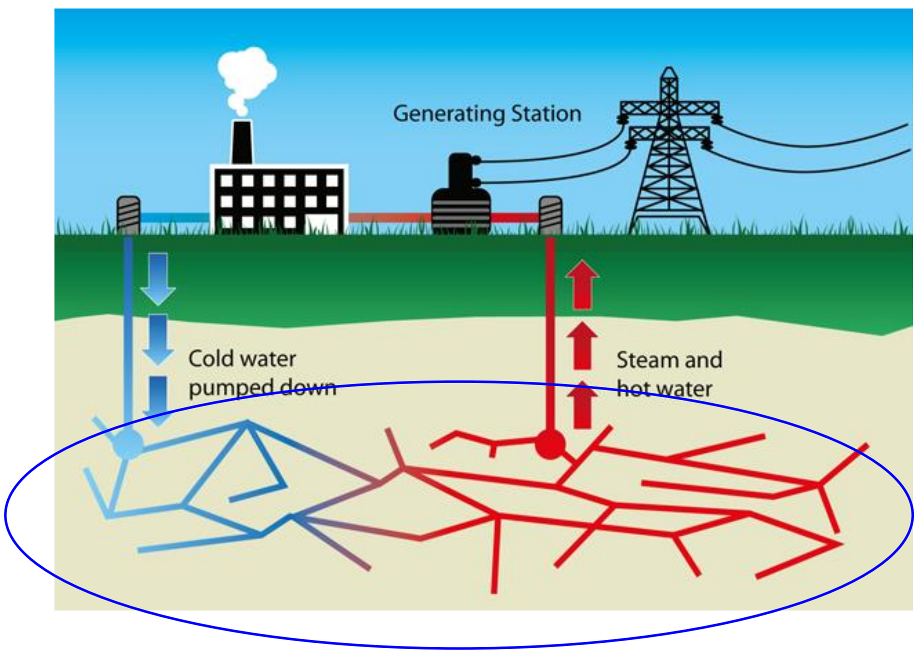
Outline

- Introduction
- Synthetic test
- Field data
- Monitoring CO2 injection

Introduction

- Fracture detection and characterization is crucial for geothermal exploration and optimizing enhanced geothermal systems.
- Fracture zones behave as anisotropic media for seismic-wave propagation.
- We develop a novel anisotropic RTM method for reliable imaging of fracture zones.
- We apply our anisotropic RTM method to field seismic data to verify its improved imaging capability.





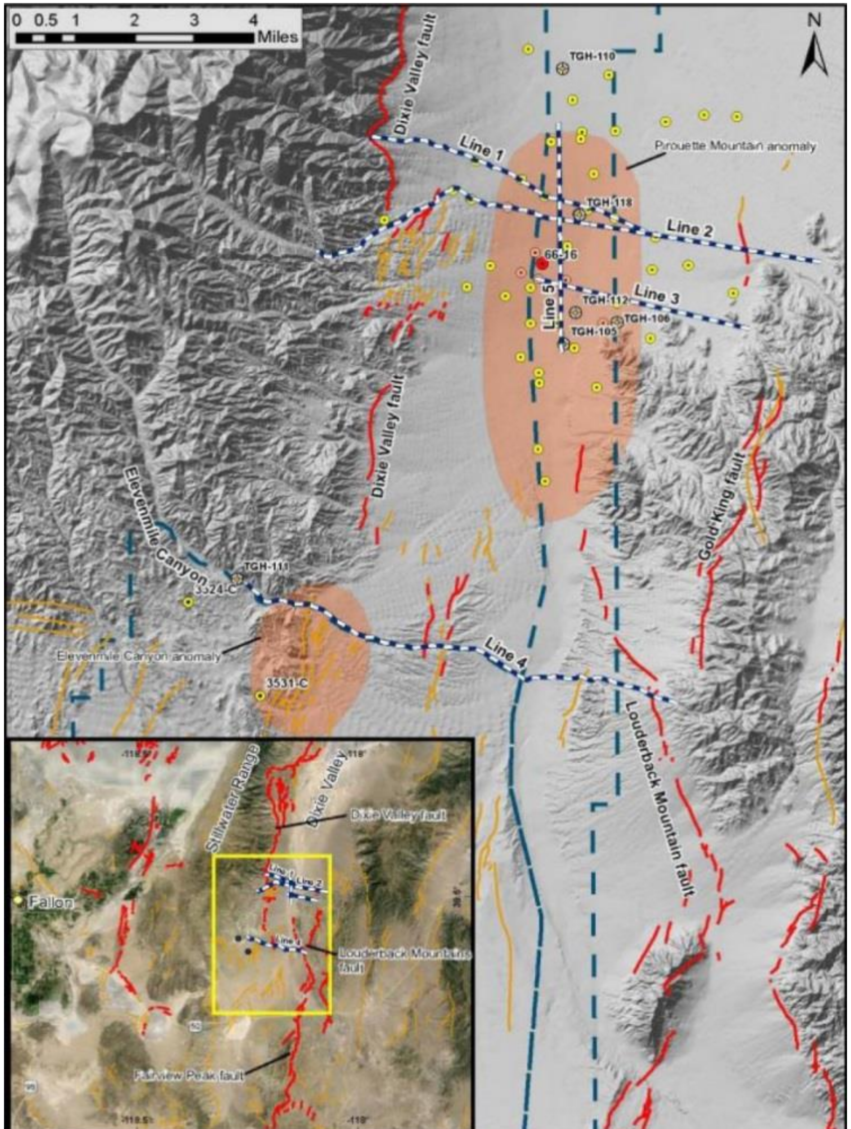
Geothermal power is cost-effective, reliable, sustainable, and environmentally friendly.

Heat energy → Electricity

It is important to image the subsurface fracture zones for interpretations of the extensional structure generating heat flow capacity in the geothermal system.

Fracture zones behave as anisotropic media for seismic-wave propagation.

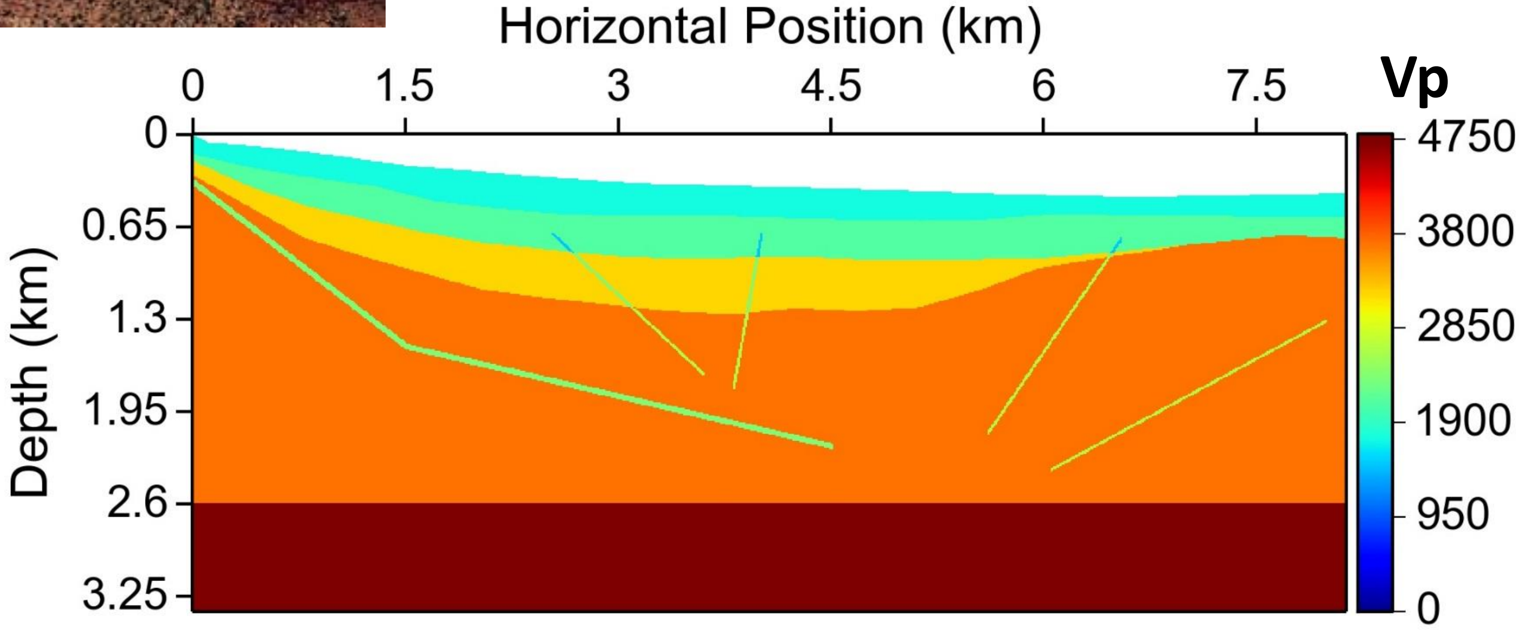
Eleven-Mile Canyon geothermal field



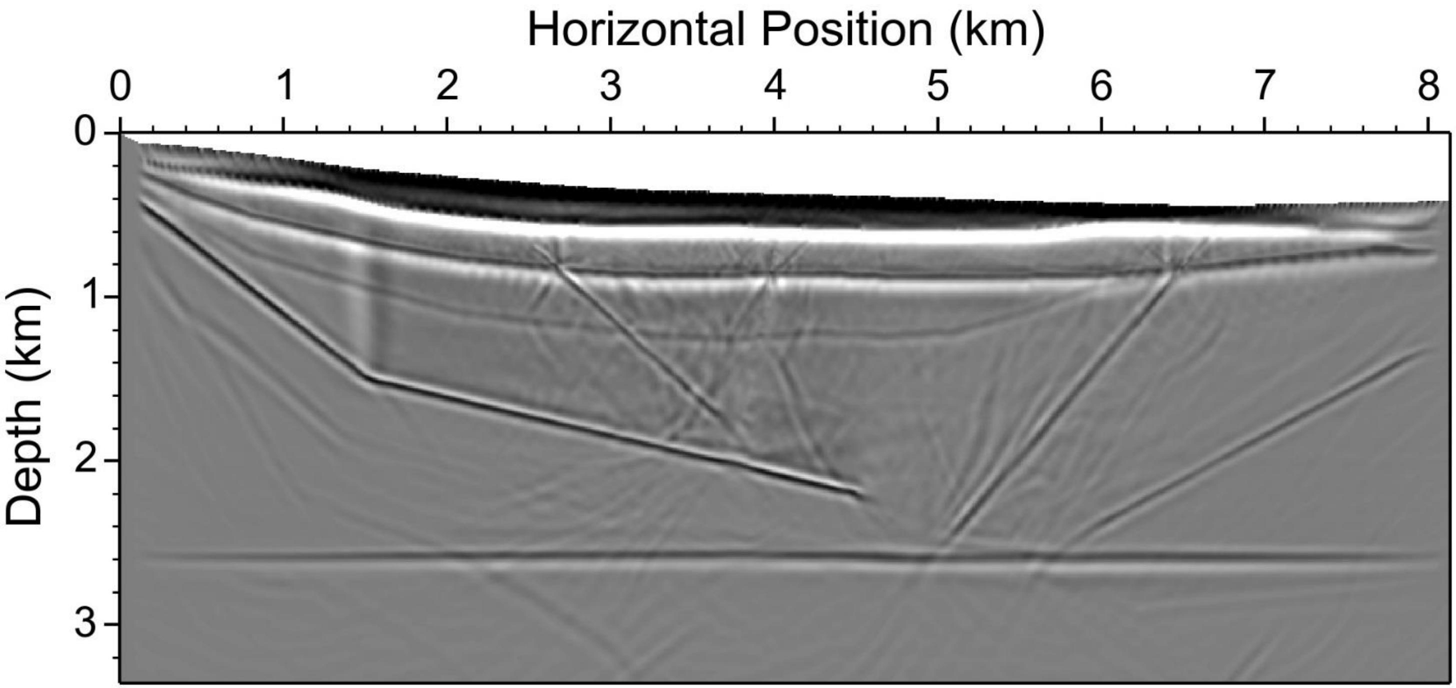
The Eleven-Mile Canyon geothermal exploration field is located near the margins of Dixie Valley, 100 kilometers east of Fallon, Nevada.

- Operated by US Navy Geothermal Program Office
- Five 2D seismic reflection lines were conducted in 2013 to evaluate geothermal potential
- Only the vertical component of seismic data were acquired at Eleven-Mile Canyon
- We assume the subsurface media contain weak anisotropy described using Thomsen parameters

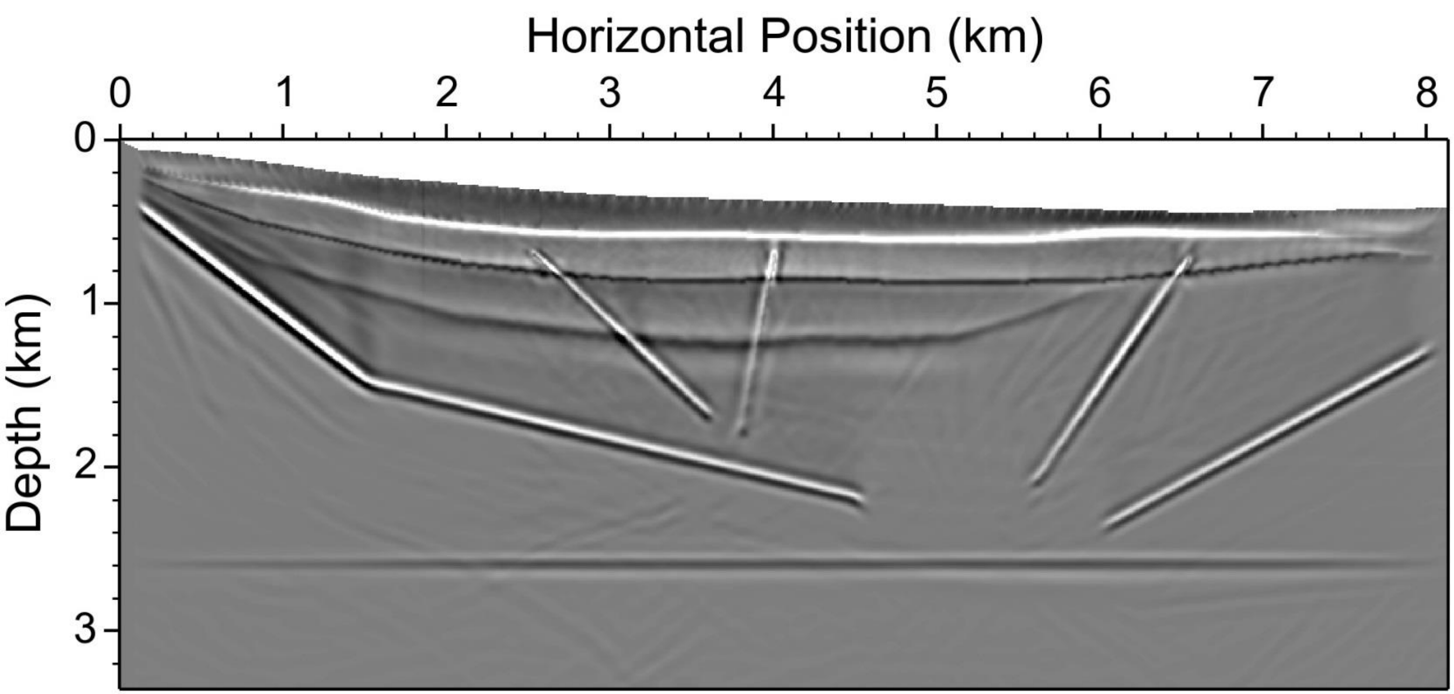
Seismic anisotropy



Synthetic test:
P wave propagation along the horizontal direction is 20% faster than that along the vertical direction (VTI)

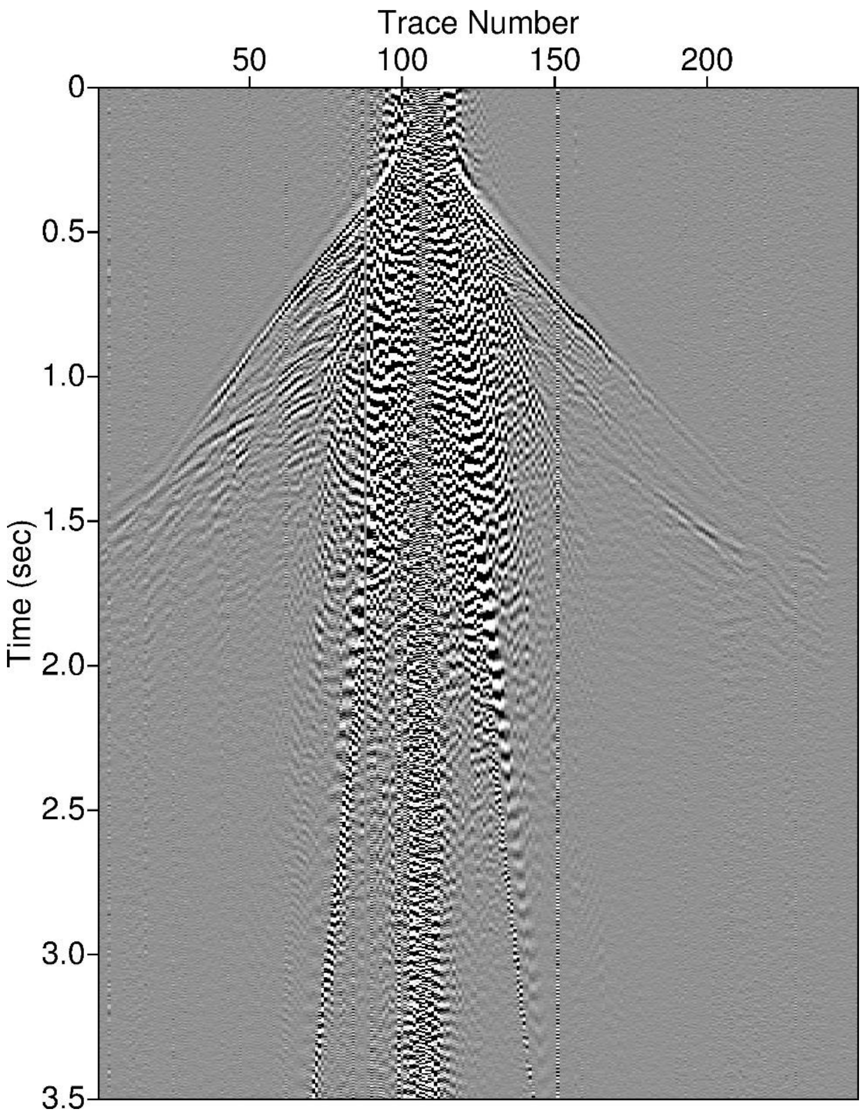


Isotropic PP Image



Anisotropic PP Image

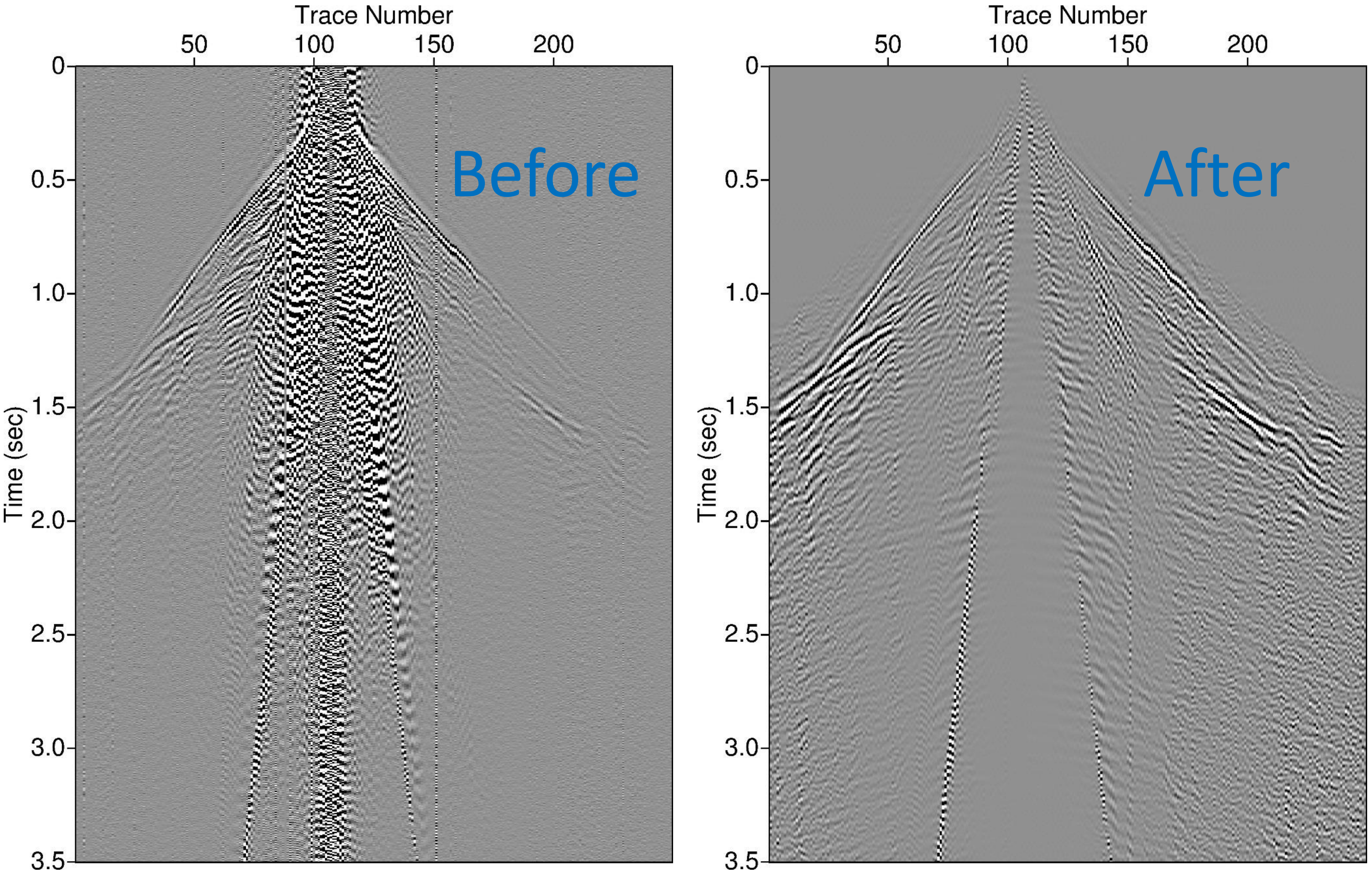
Data processing



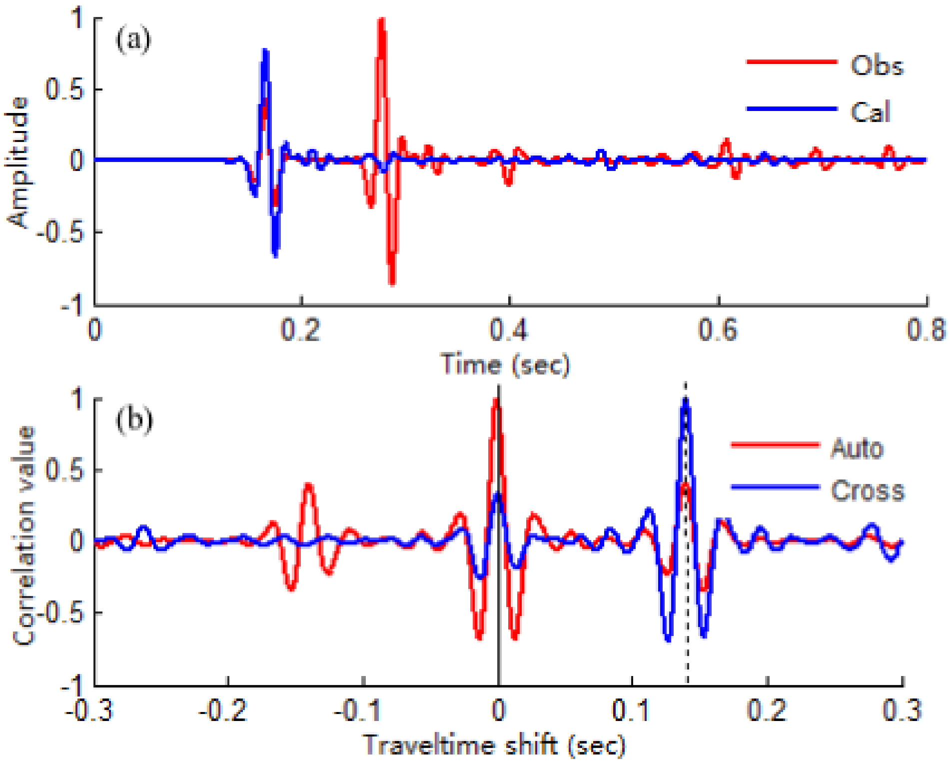
Data processing:

1. remove dead traces
2. bandpass filtering
3. trace balancing
4. geometrical spreading correction
5. removing ground roll noise

Data processing



An optimized correlation-based full waveform inversion

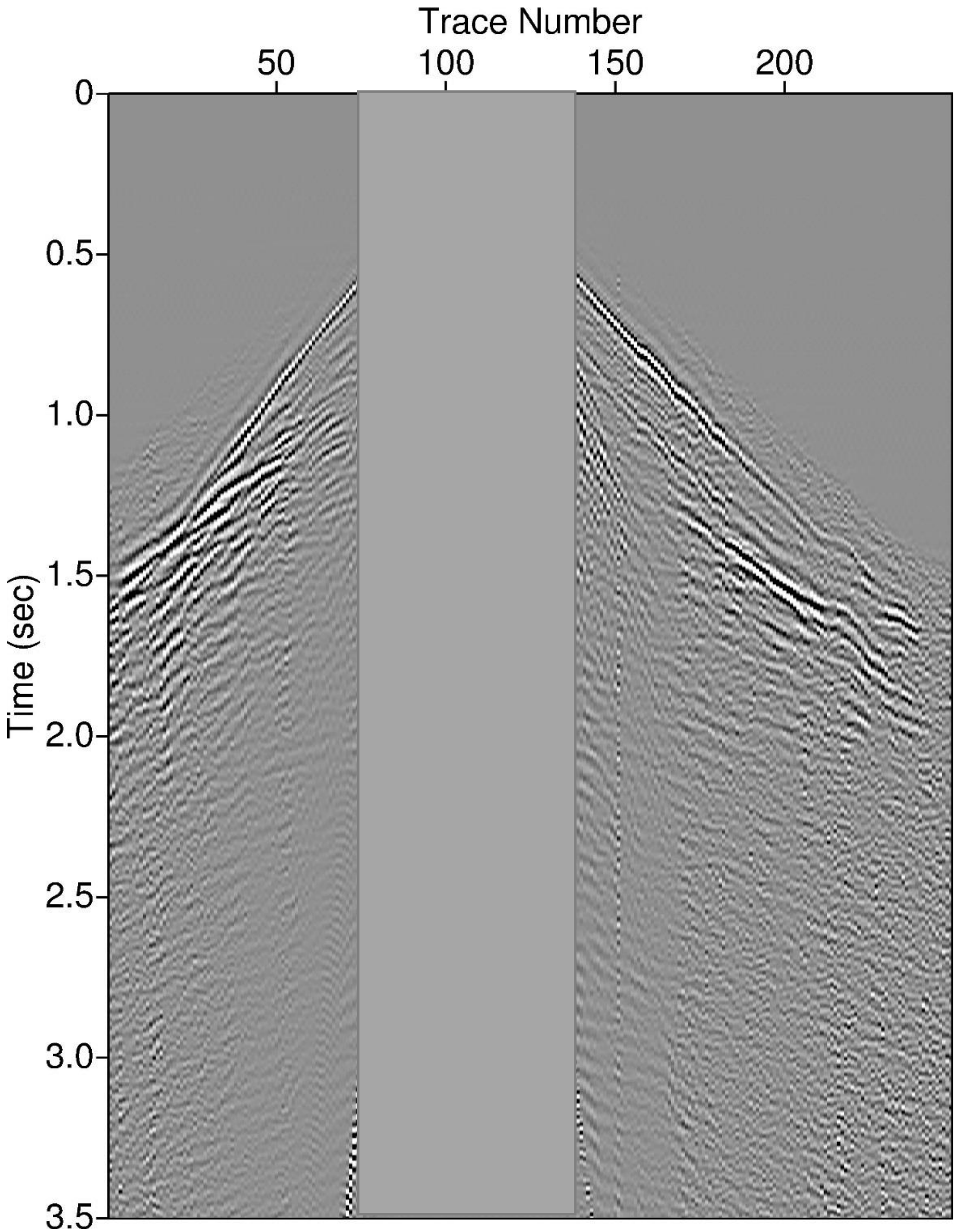


$$E_1 = \sum_{shot}\sum_{recv}\sum_{\tau}\left[W(\tau)\cdot\left\{C[\hat{d},\hat{d}](\tau) - C[\hat{u},\hat{d}](\tau)\right\}\right]^2$$

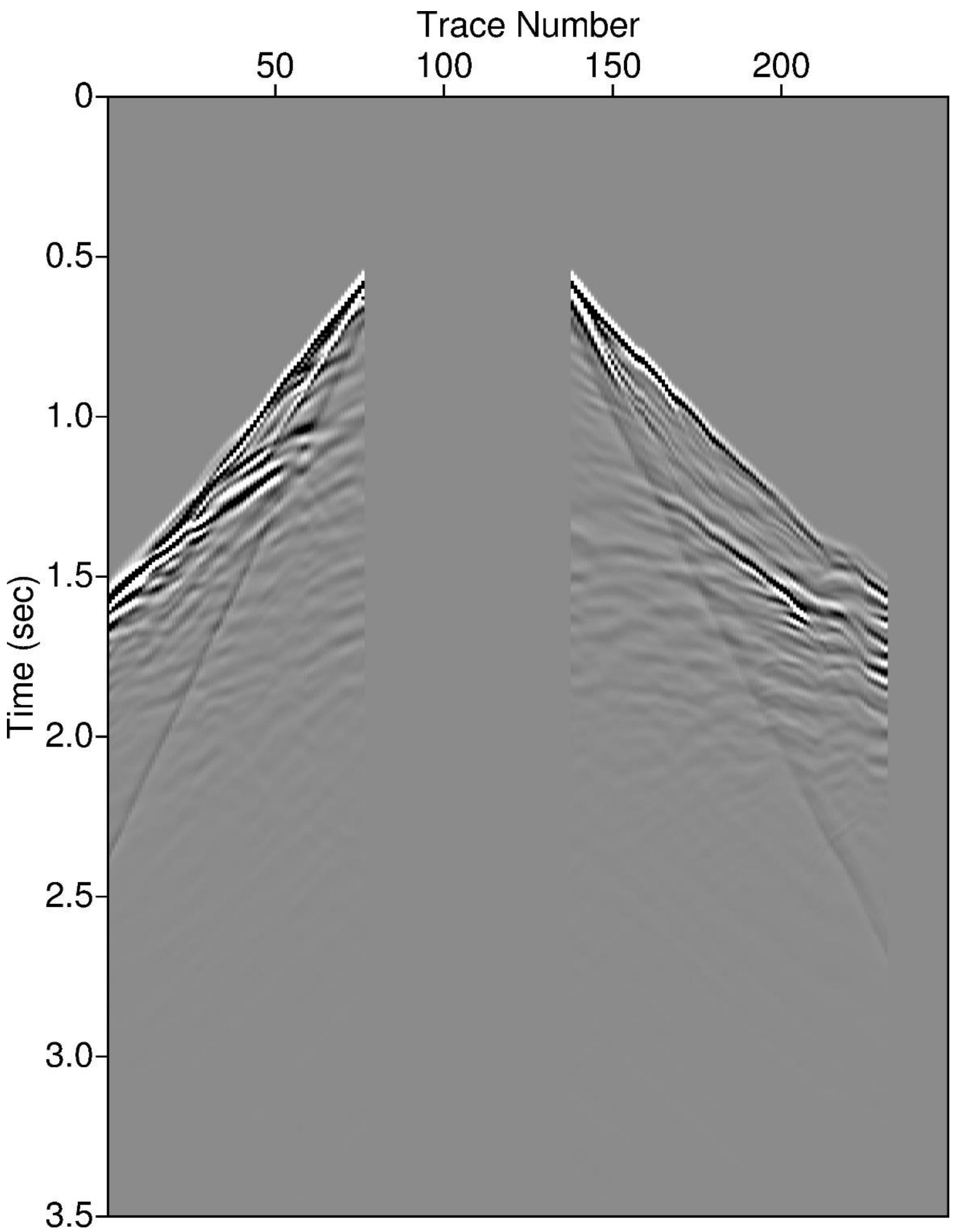
$$E_2 = \sum_{shot}\sum_{recv}\sum_{\tau}\left[-W(\tau)\cdot C[\hat{d},\hat{d}](\tau)\cdot C[\hat{u},\hat{d}](\tau)\right].$$

Choi and Alkhalifah, EAGE, 2016;
Yi and Liu, SEG, 2017

Obs.

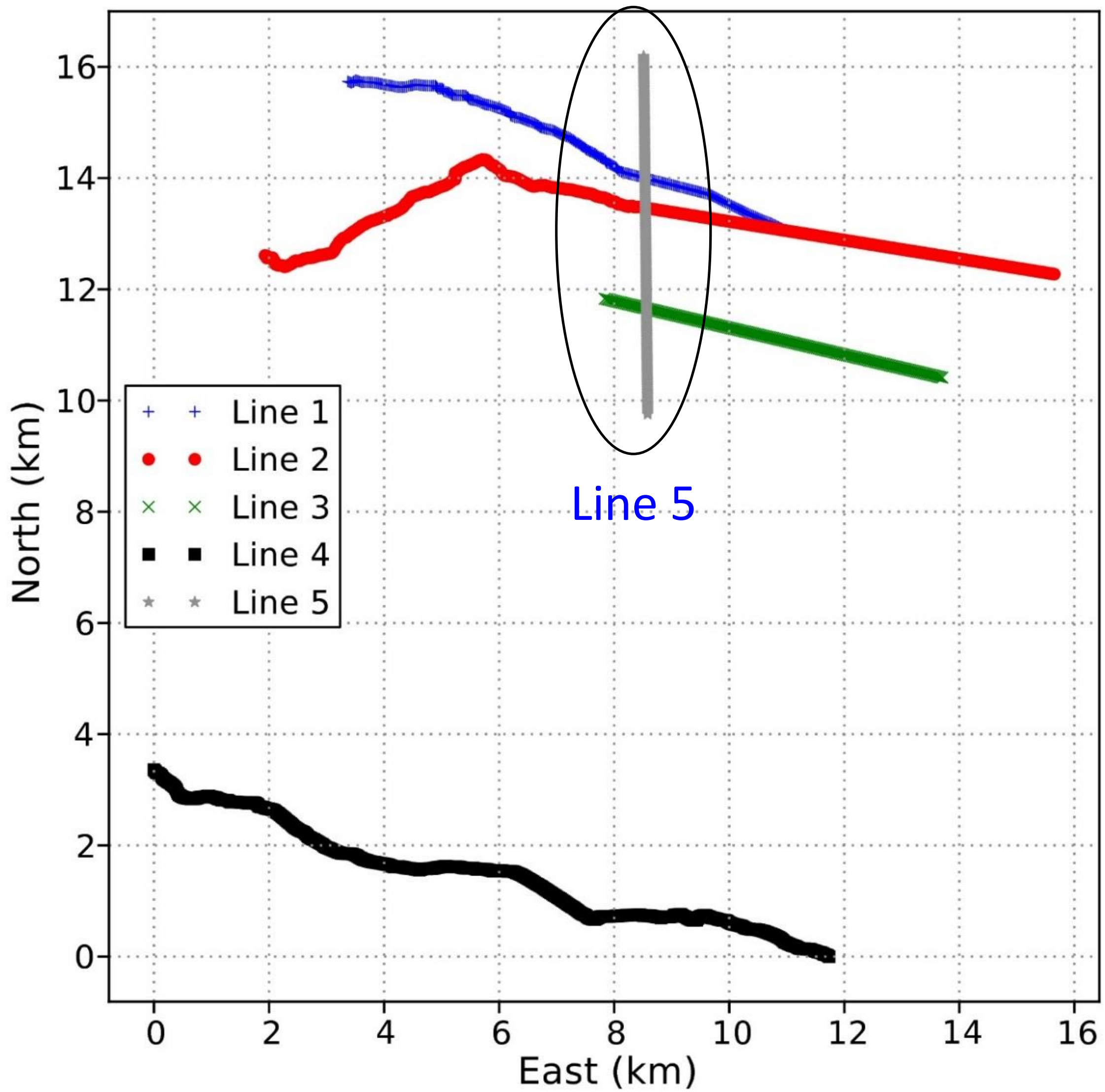


Syn.



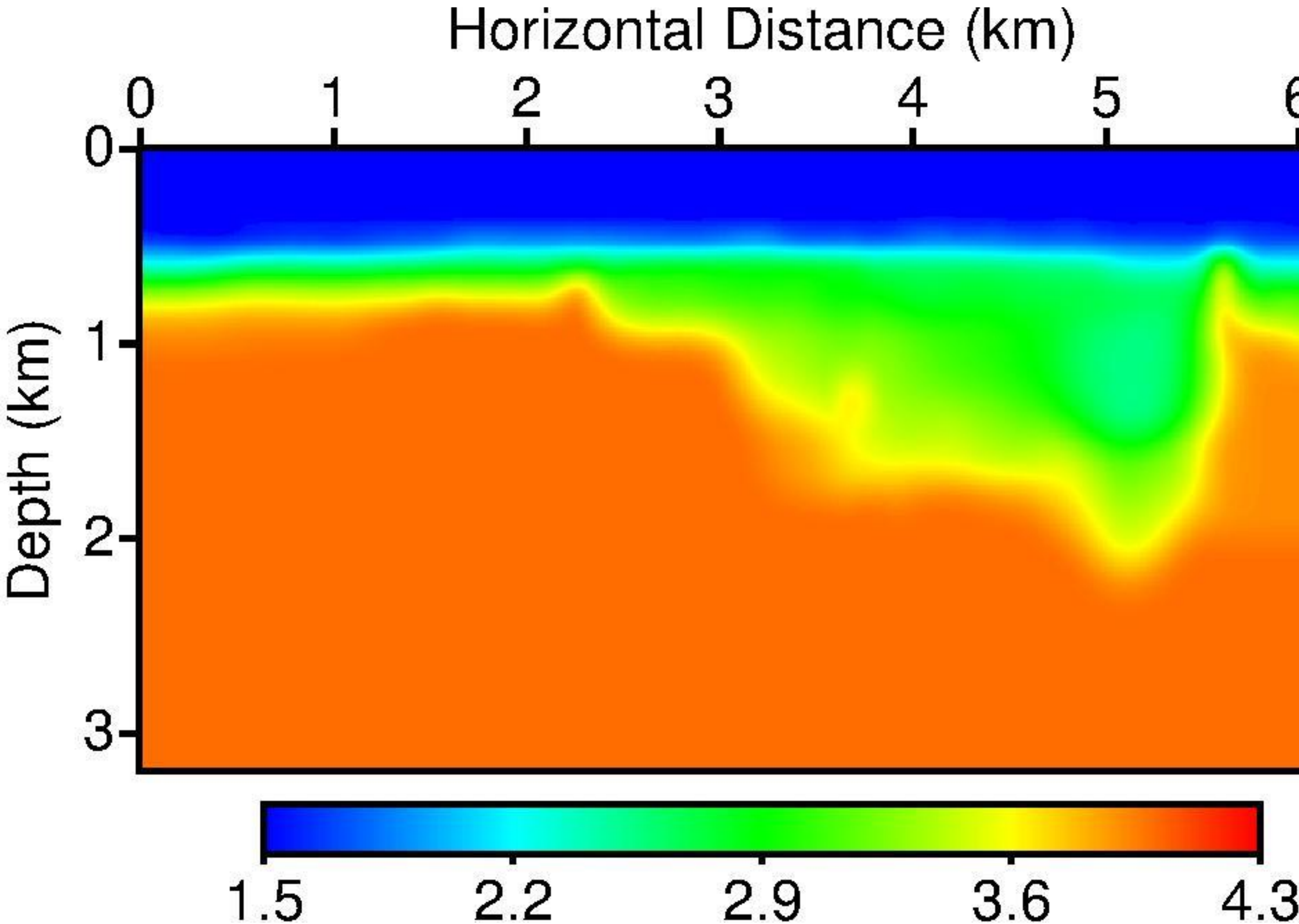
Workflow

1) Process the raw seismic data for each line
2) Update isotropic Vp using the optimized correlation-based FWI and initial model inferred from traveltime tomography
3) Estimate the initial theta parameter (dip angle) from reverse-time migration image
4) Invert Thomsen parameters using the same FWI method based on the updated isotropic Vp and initial theta
5) Image subsurface fracture zones using anisotropic reverse-time migration and inverted anisotropic Thomsen parameters

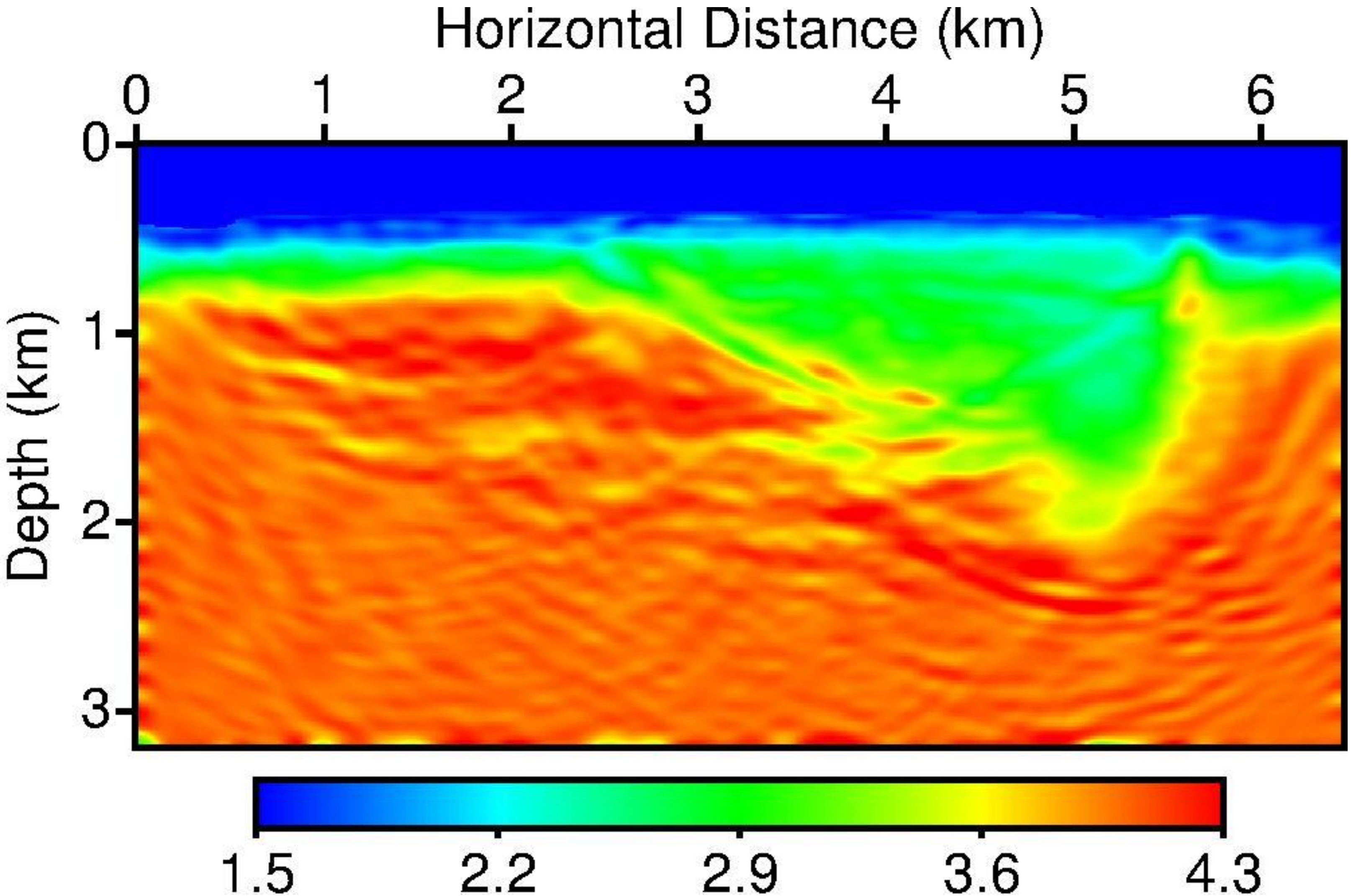


Line 1
Line 2
Line 3
Line 4
Line 5
Line 5
North (km)
East (km)
0
2
4
6
8
10
12
14
16

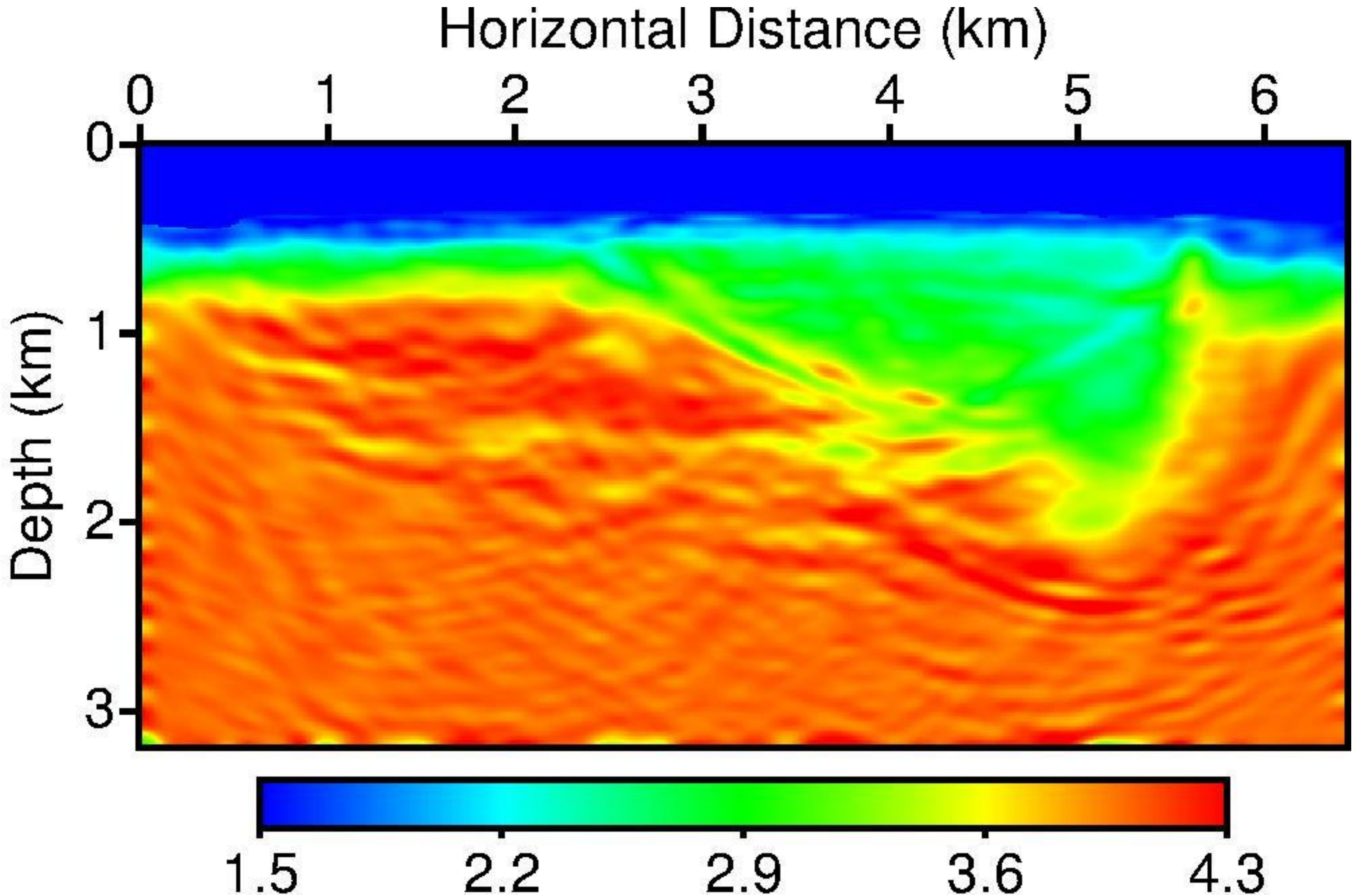
Initial Vp



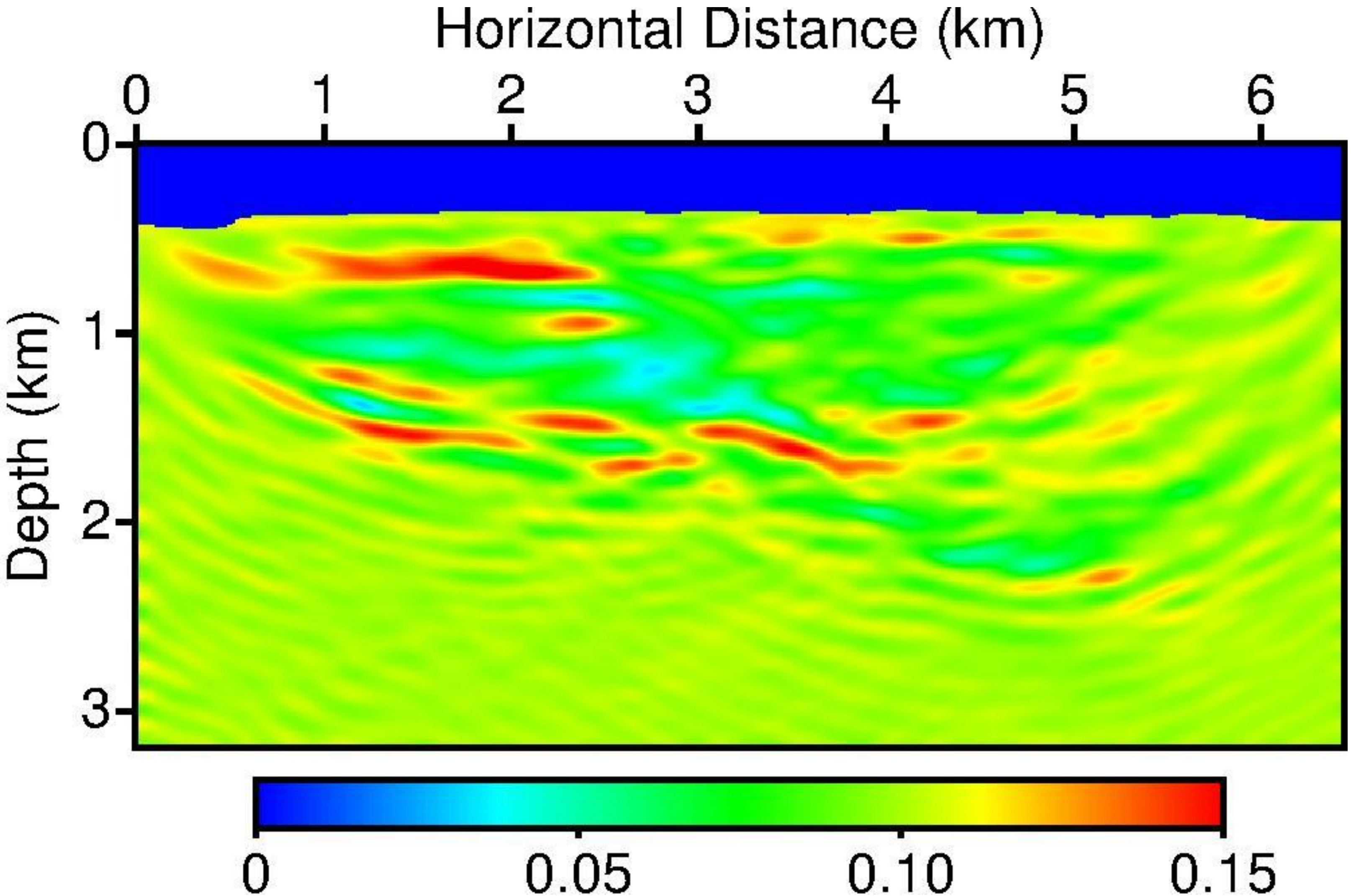
Updated isotropic Vp



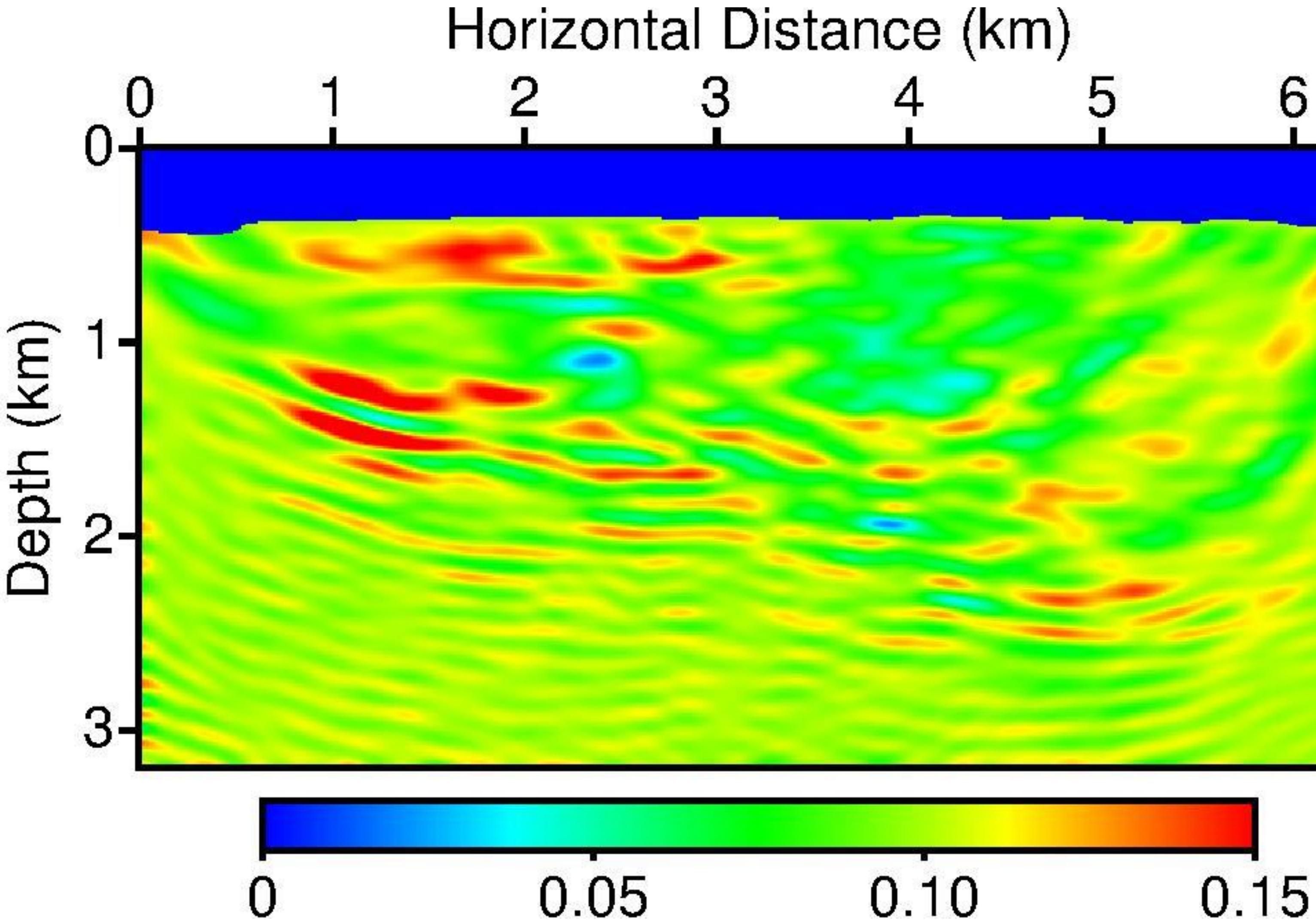
Inverted anisotropic Vp0



Inverted epsilon



Inverted delta



Inverted theta

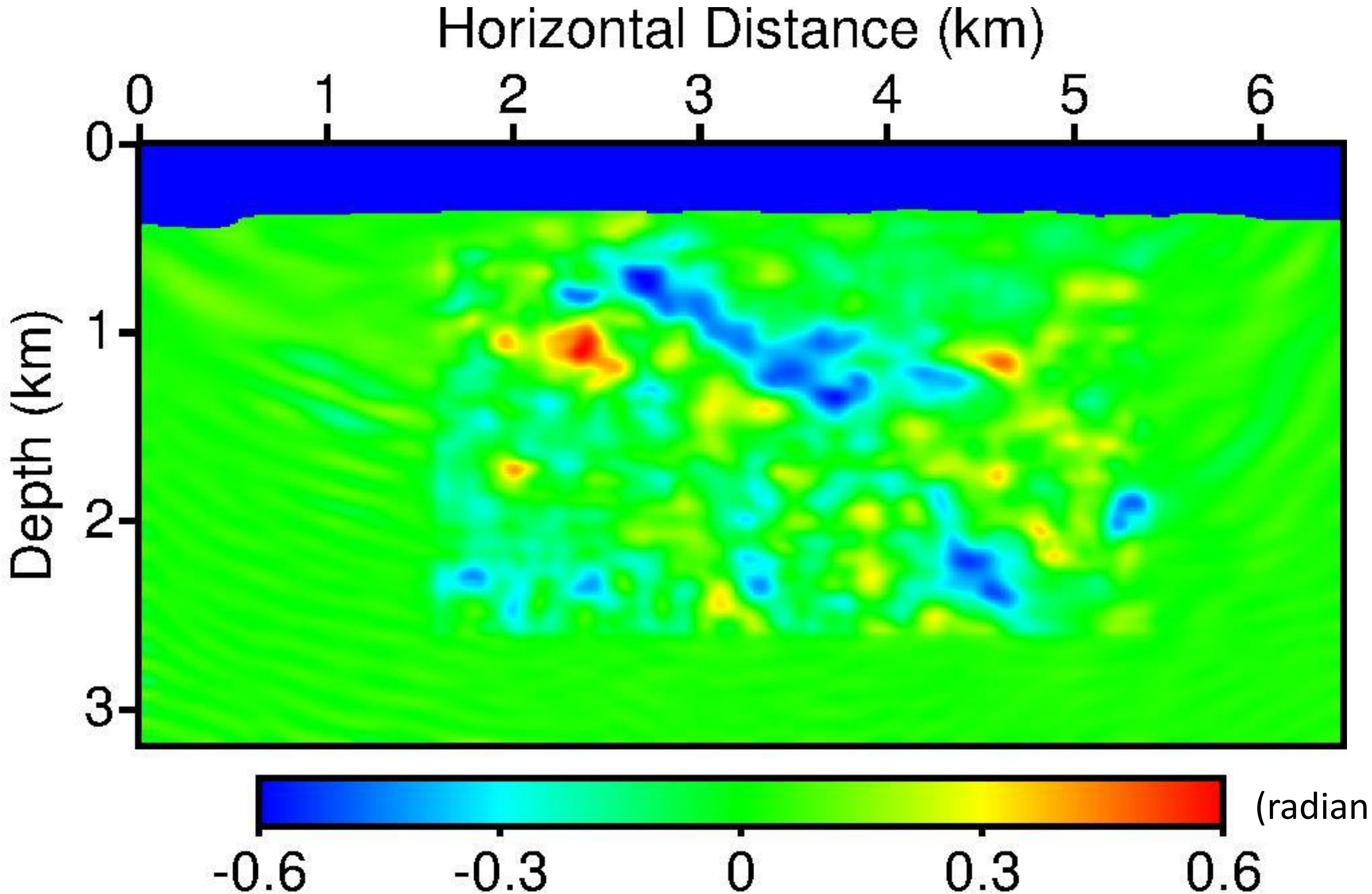


Image using initial Vp

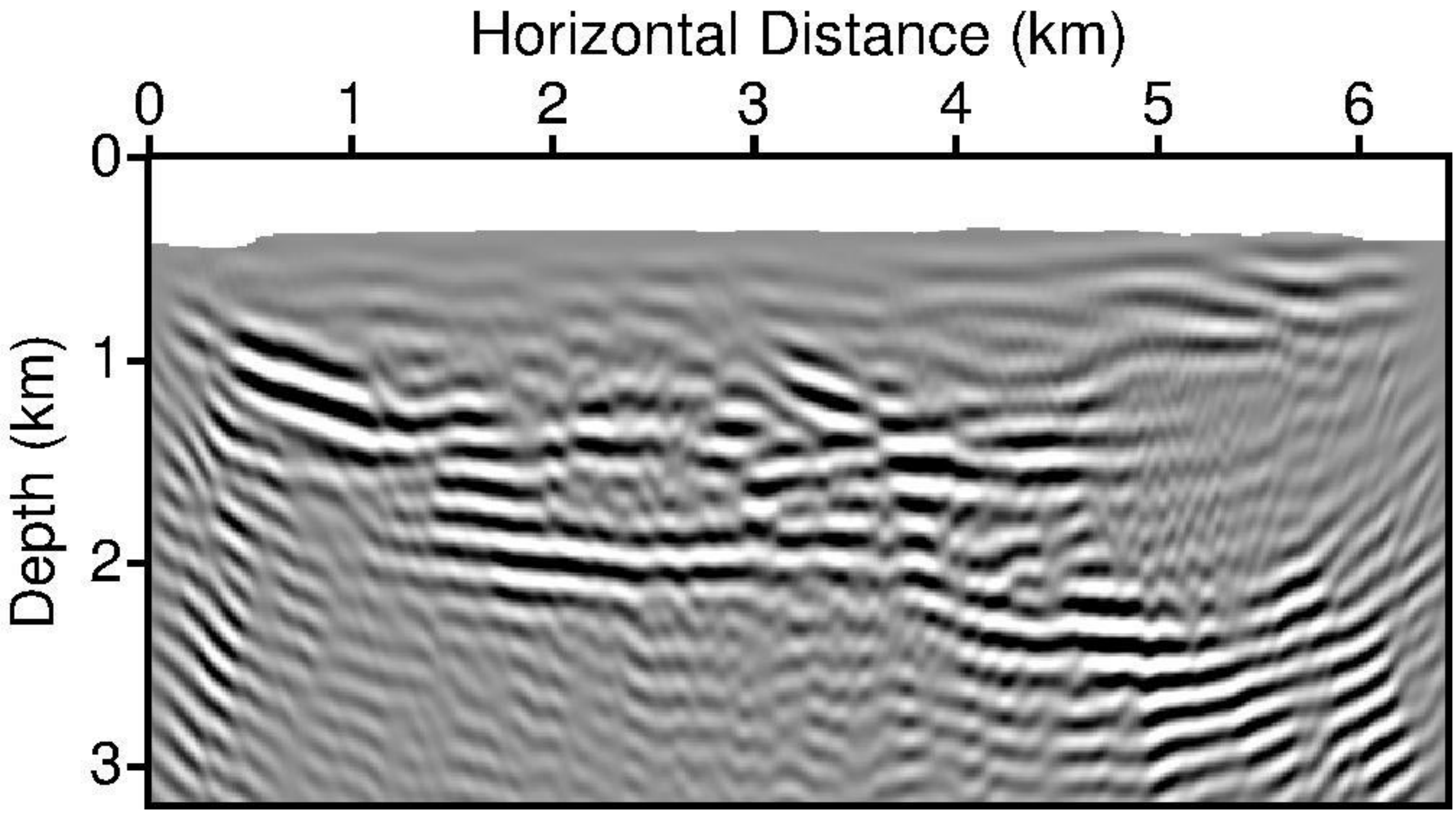


Image using updated isotropic Vp

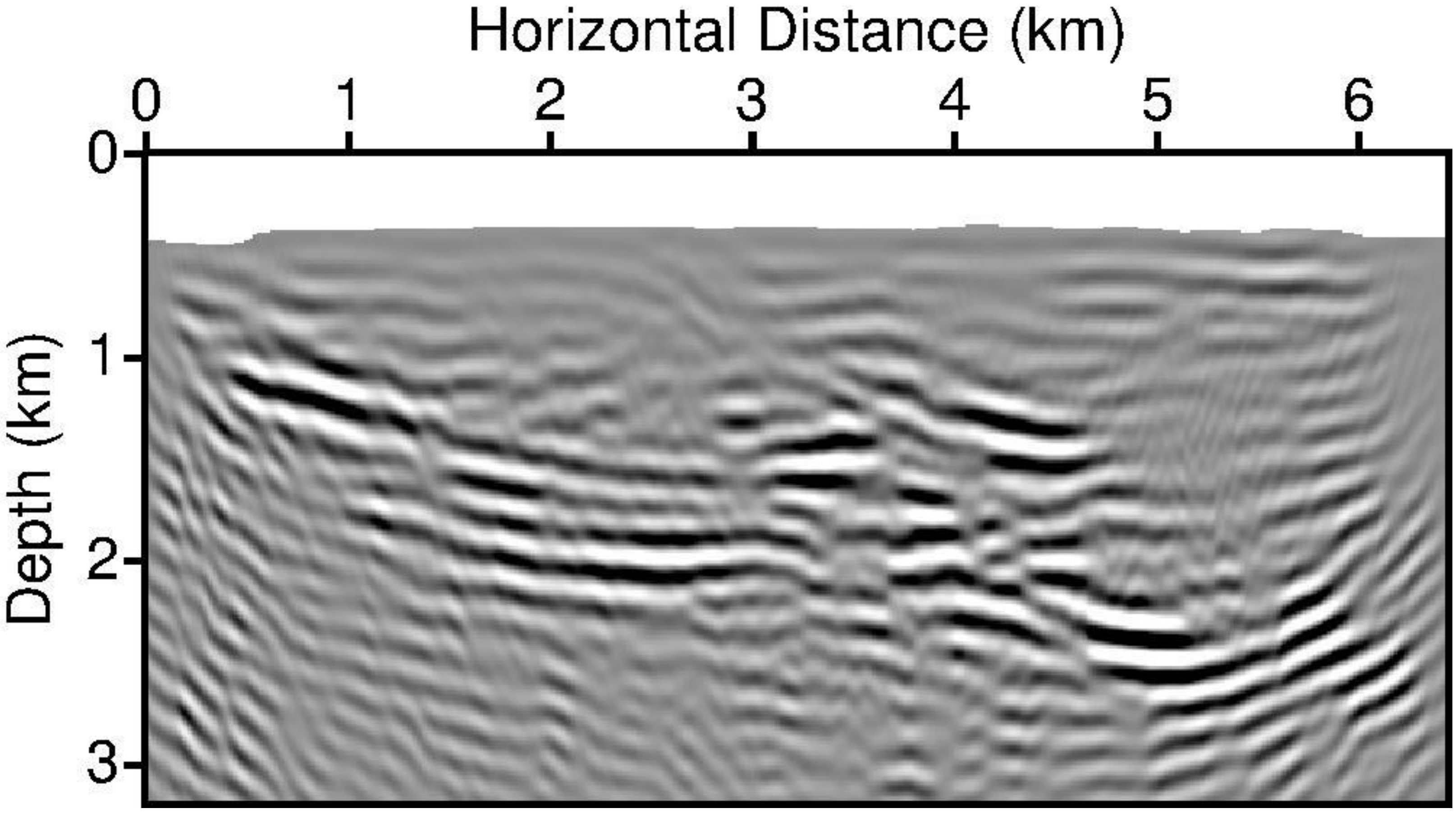
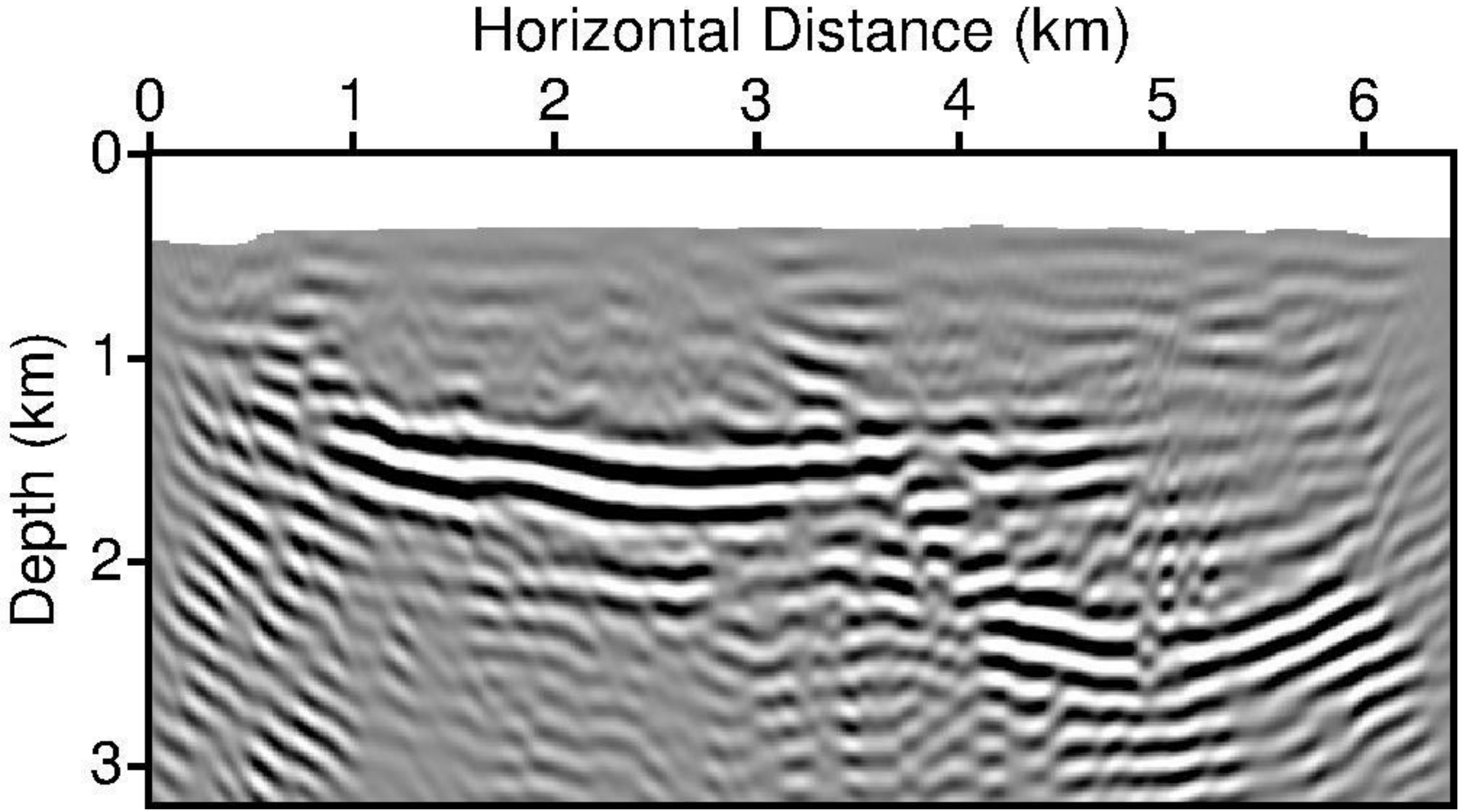
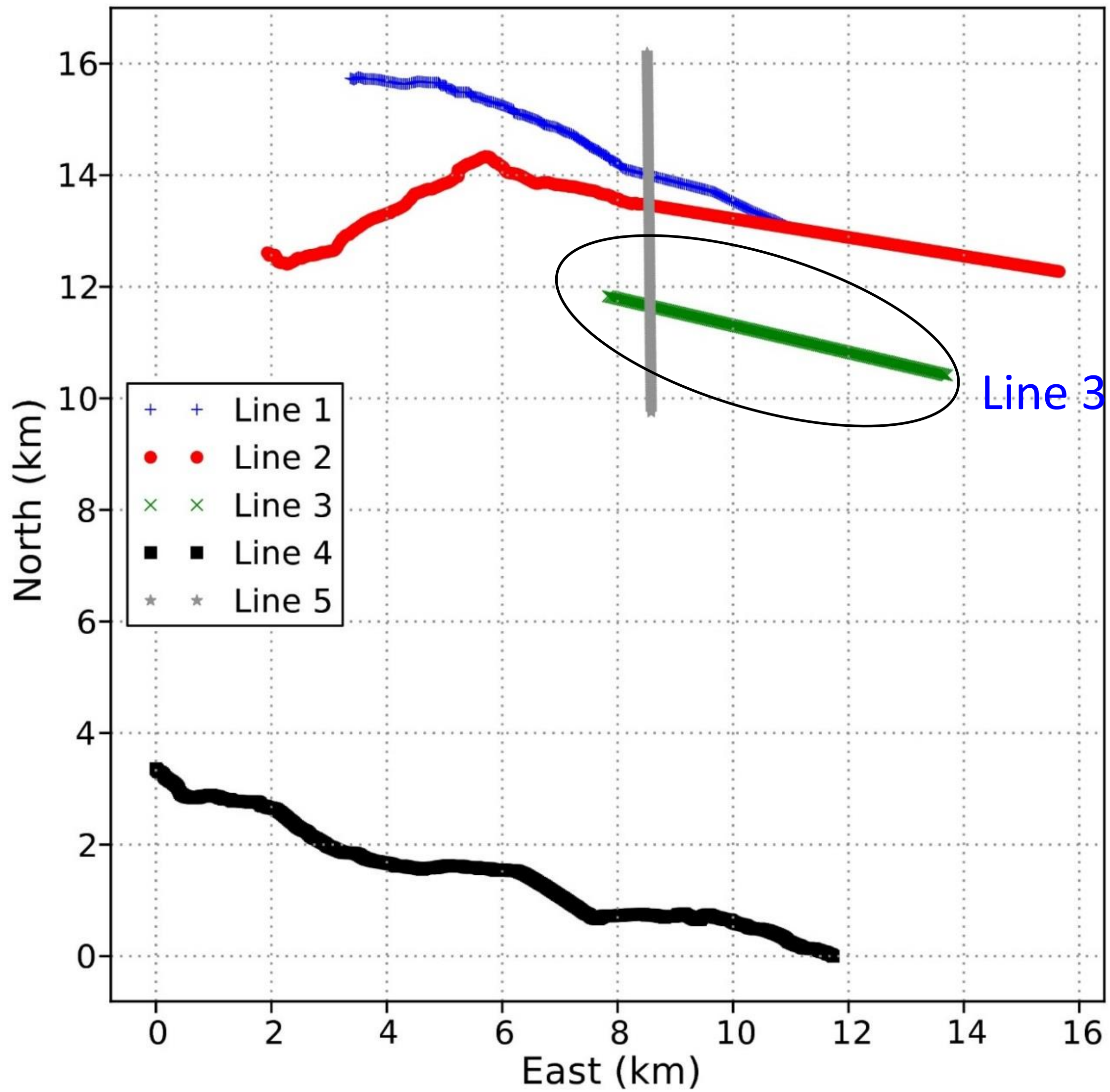


Image using updated anisotropic parameters





16
14
12
10
8
6
4
2
0
North (km)
0
2
4
6
8
10
12
14
16
East (km)
Line 1
Line 2
Line 3
Line 4
Line 5
Line 3

Image using initial Vp

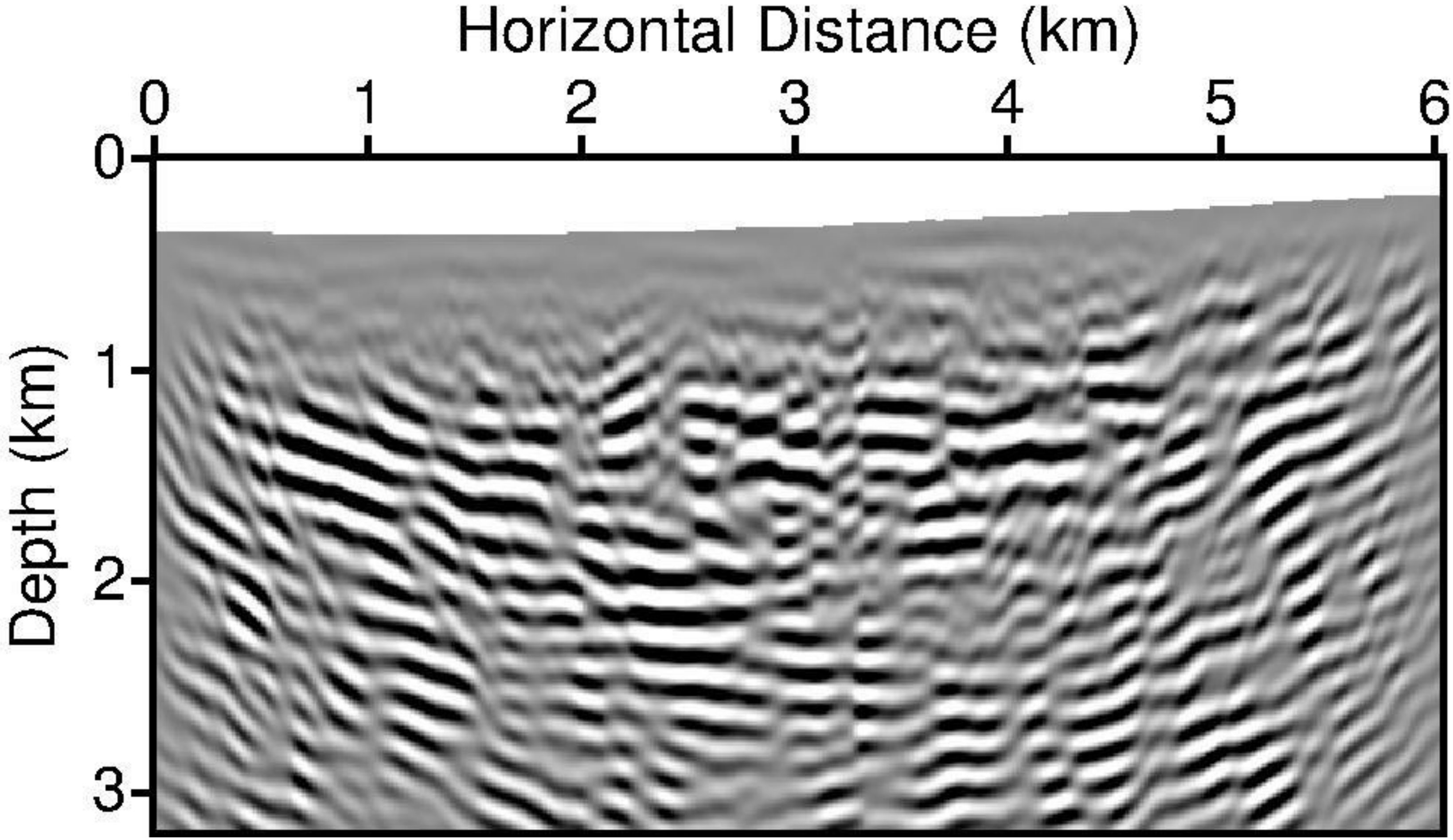


Image using updated isotropic Vp

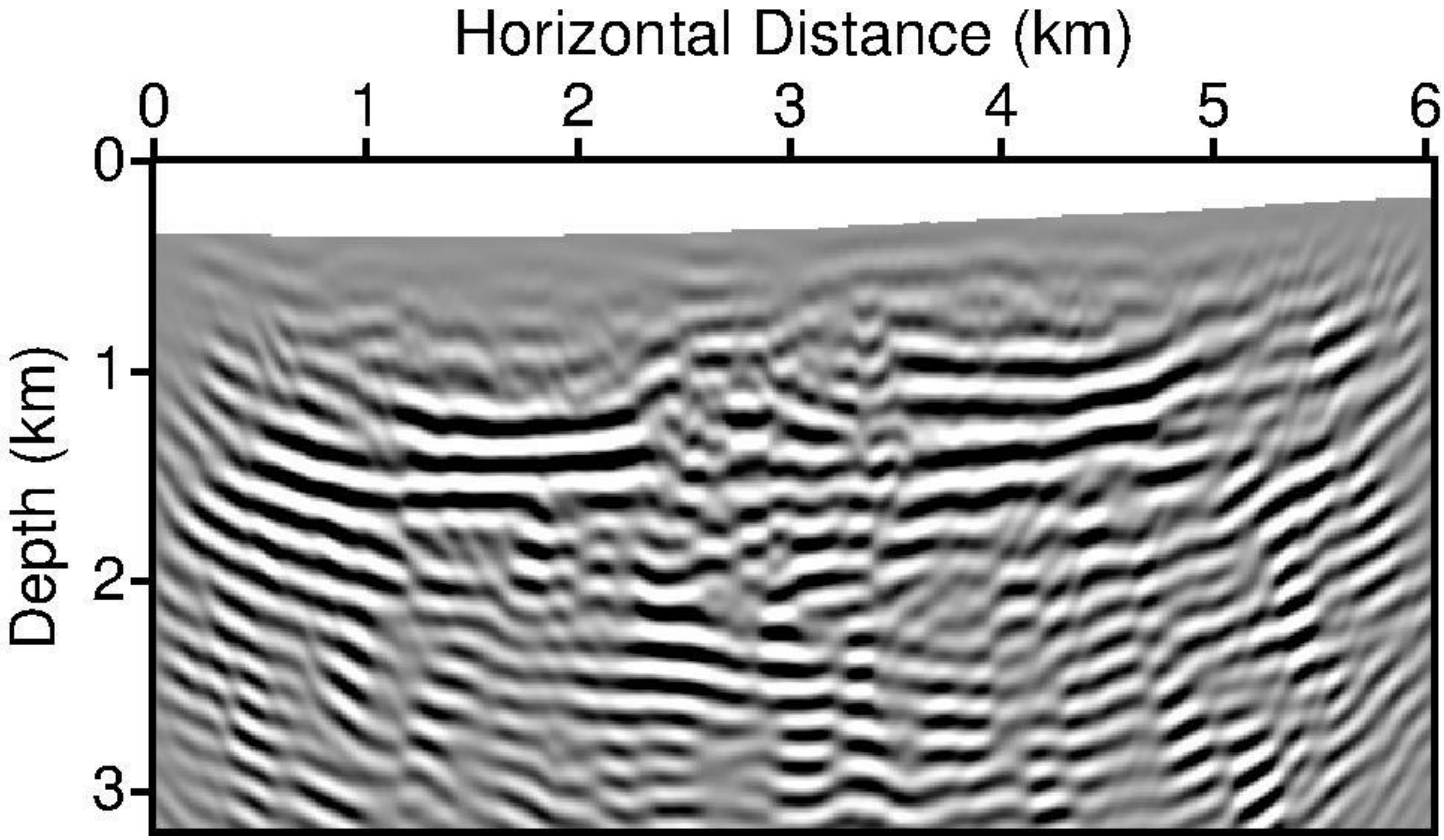
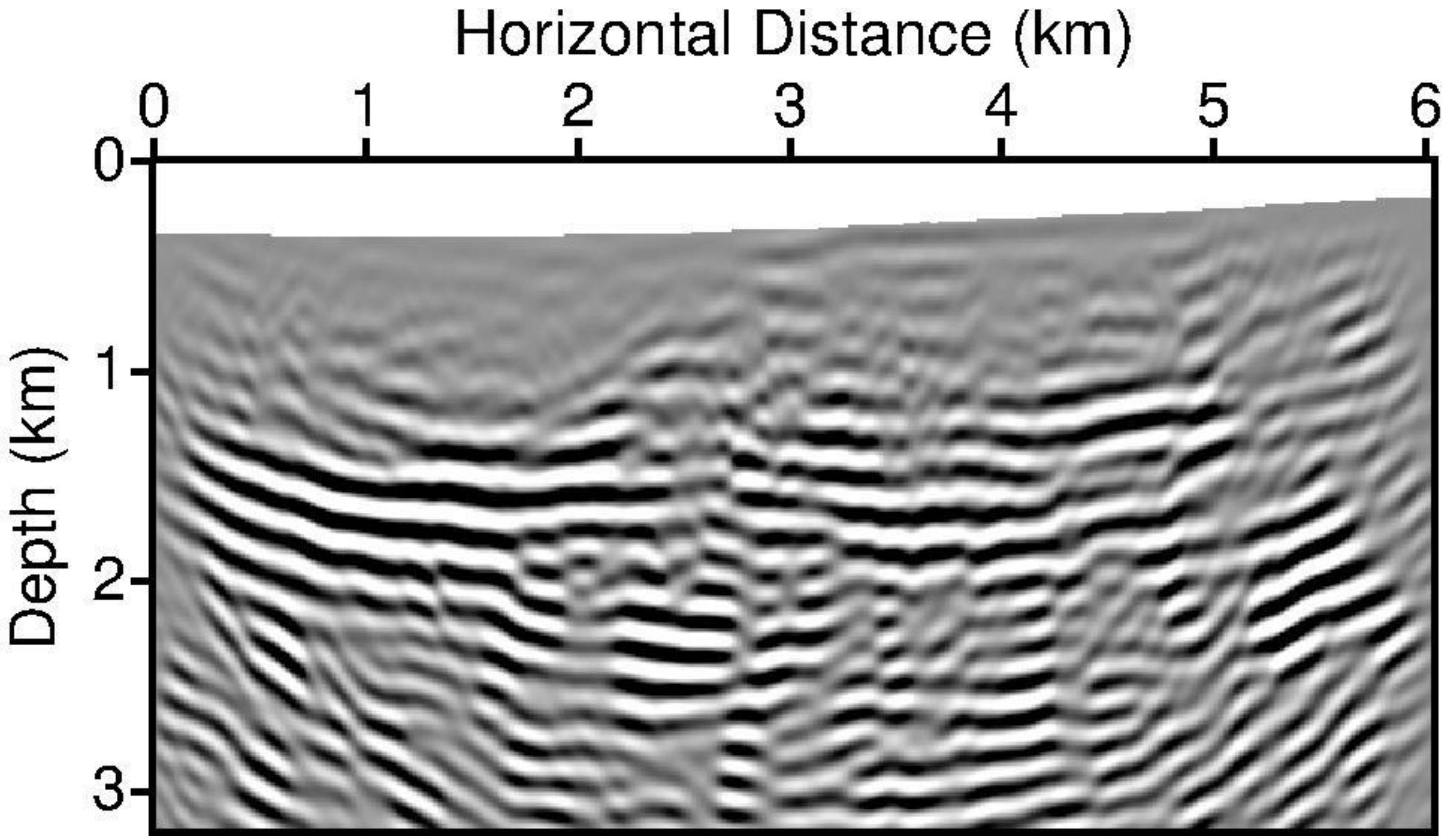
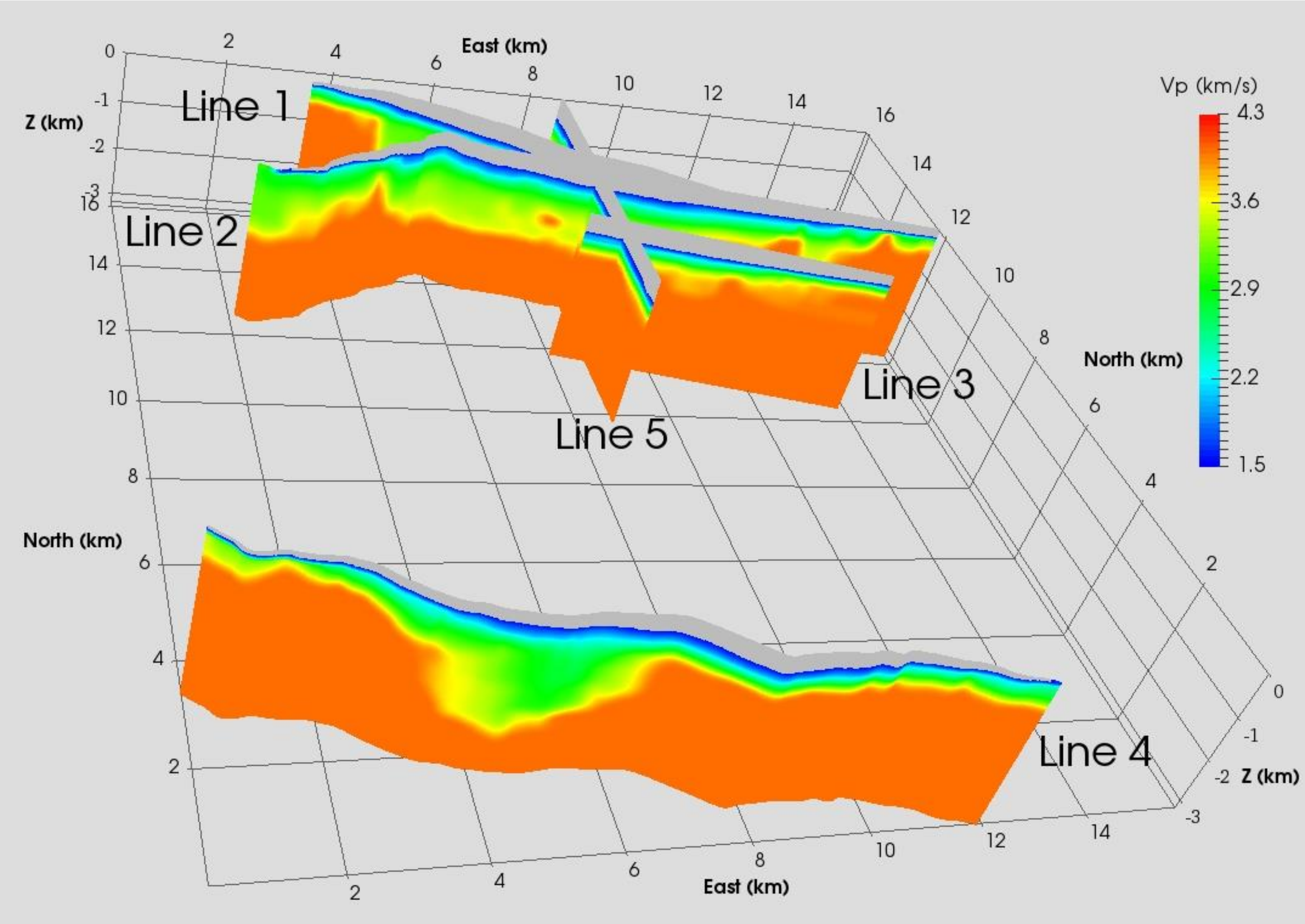


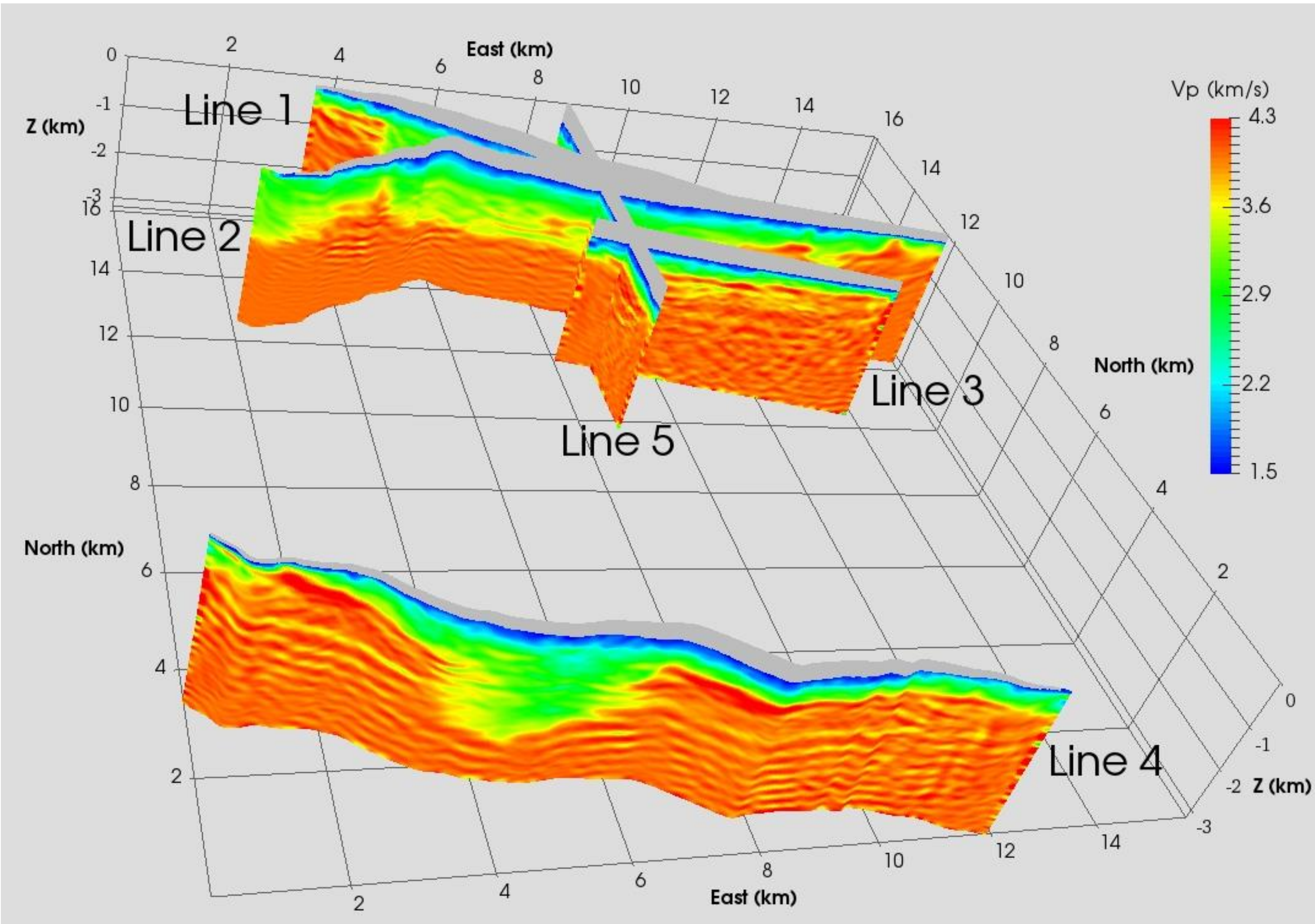
Image using updated anisotropic parameters



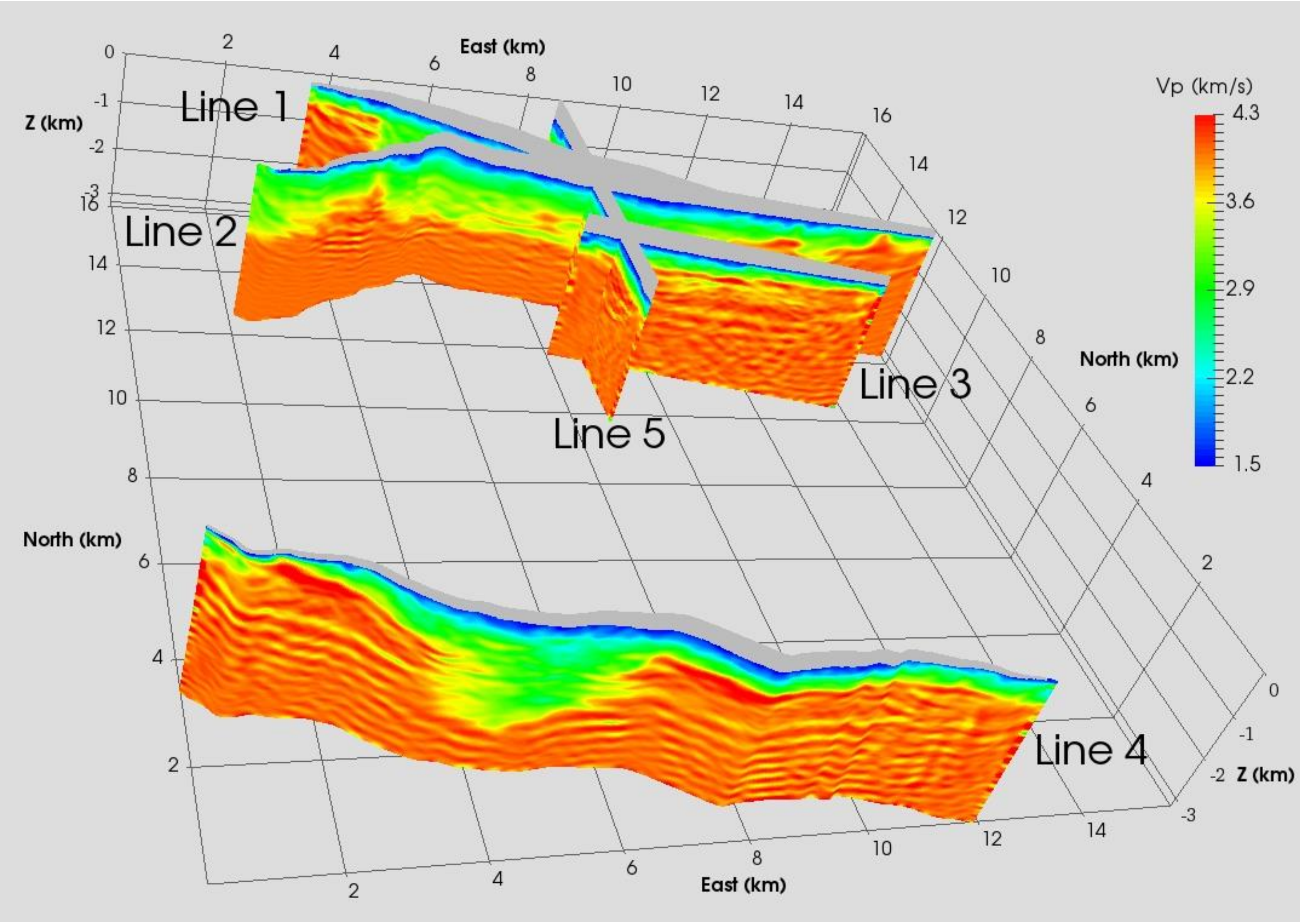
Initial Vp (3D View)



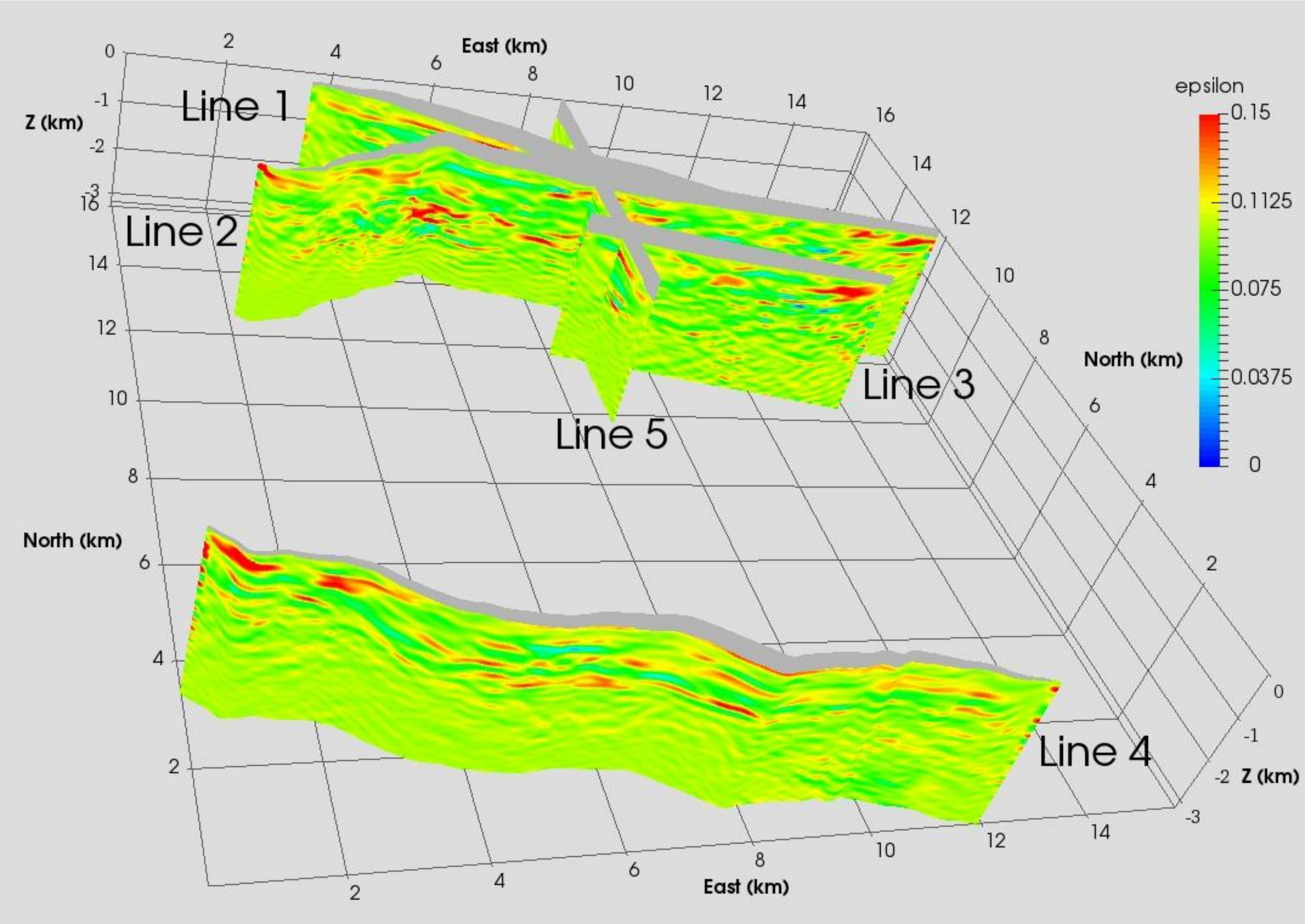
Updated isotropic Vp (3D View)



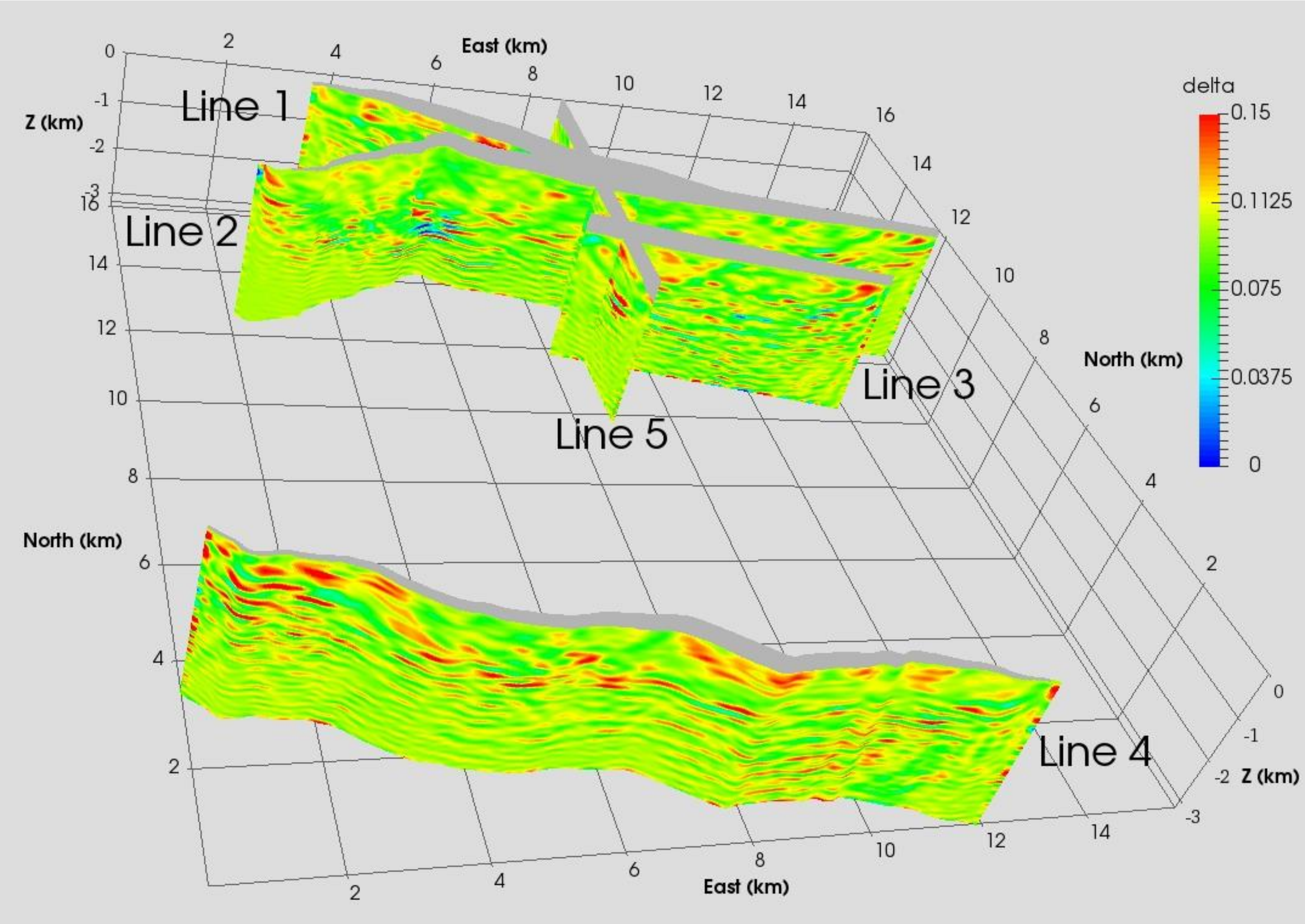
Inverted anisotropic Vp0 (3D View)



Inverted epsilon (3D View)



Inverted delta (3D View)



Inverted theta (3D View)

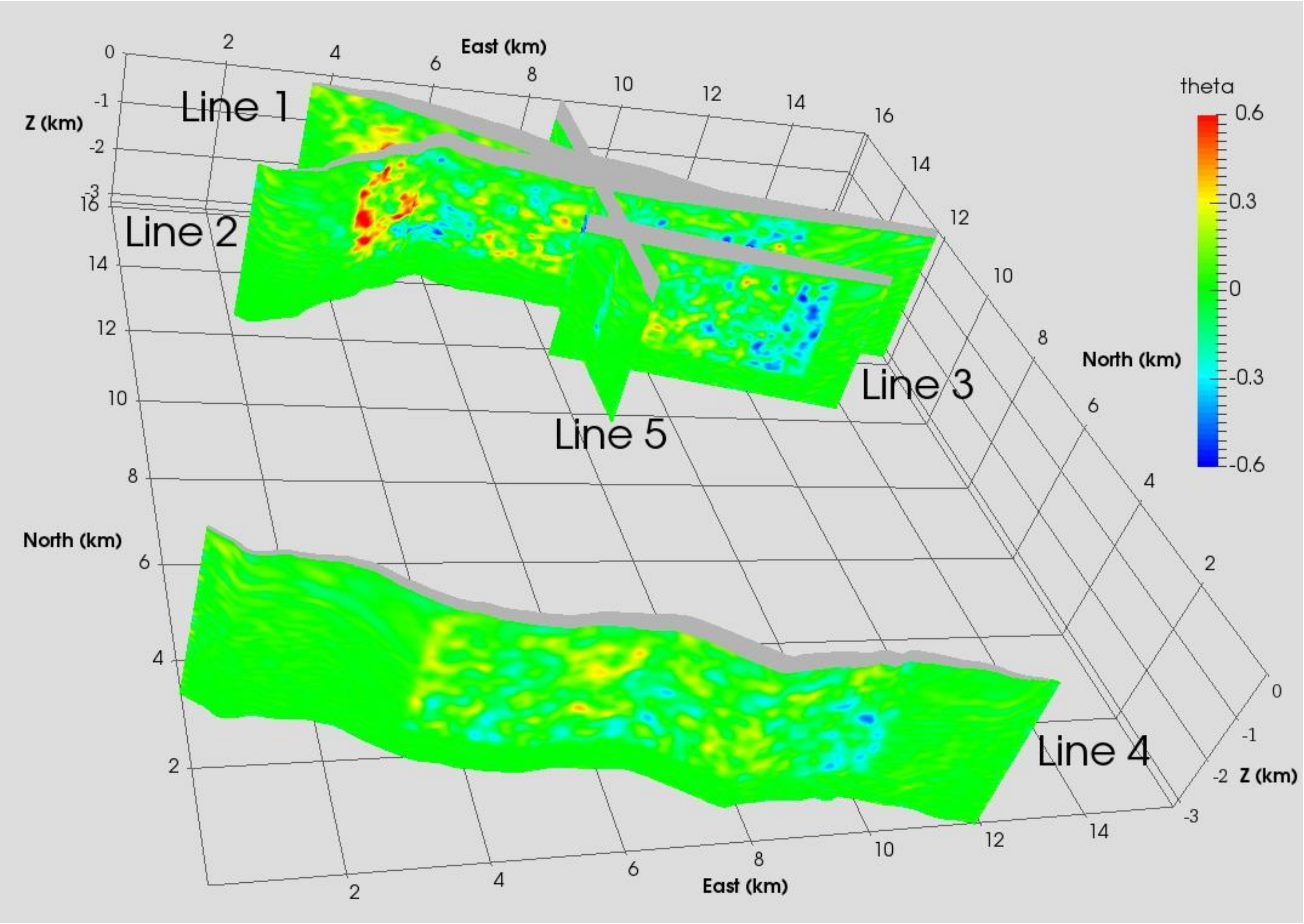


Image using initial Vp

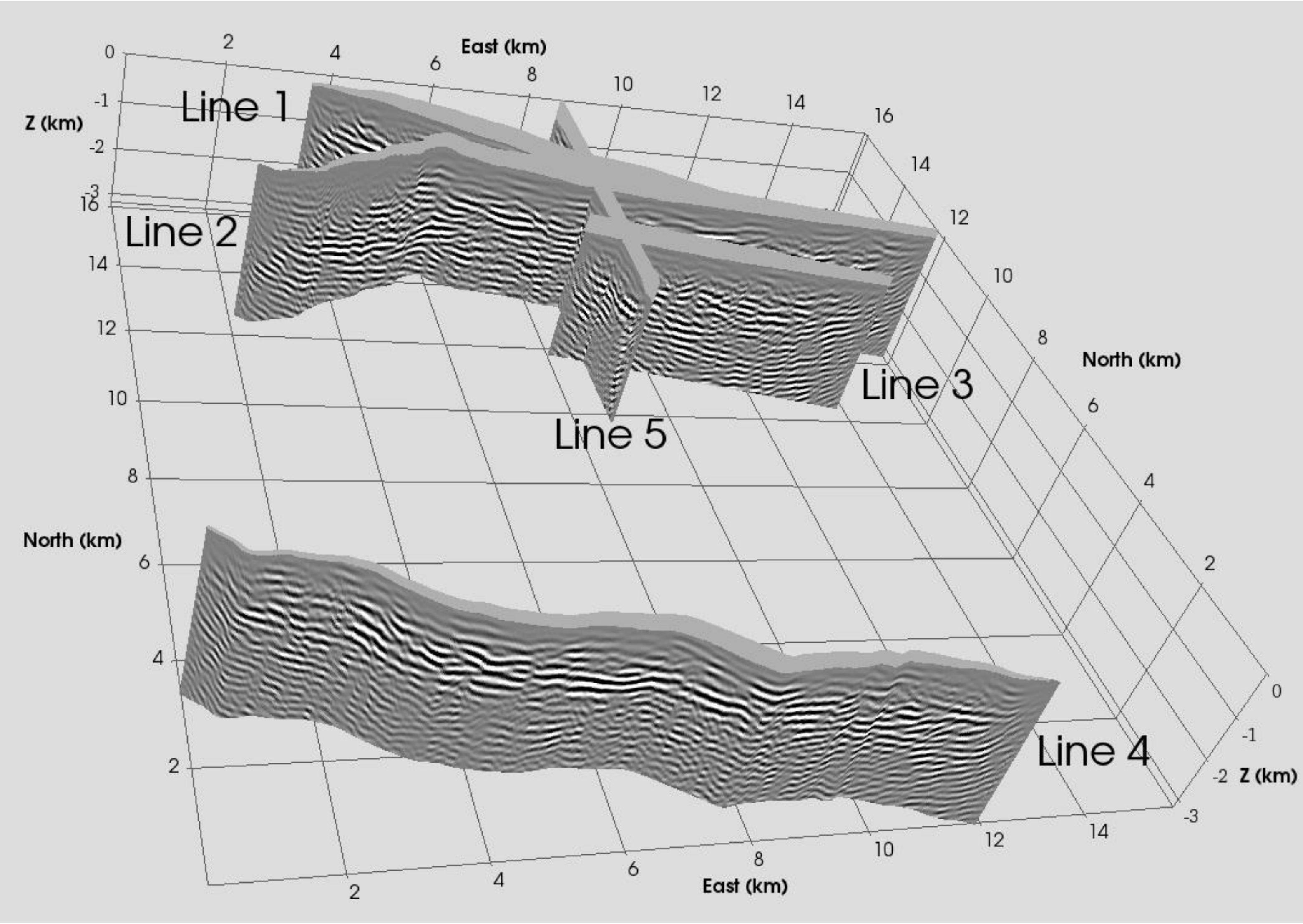


Image using updated isotropic Vp

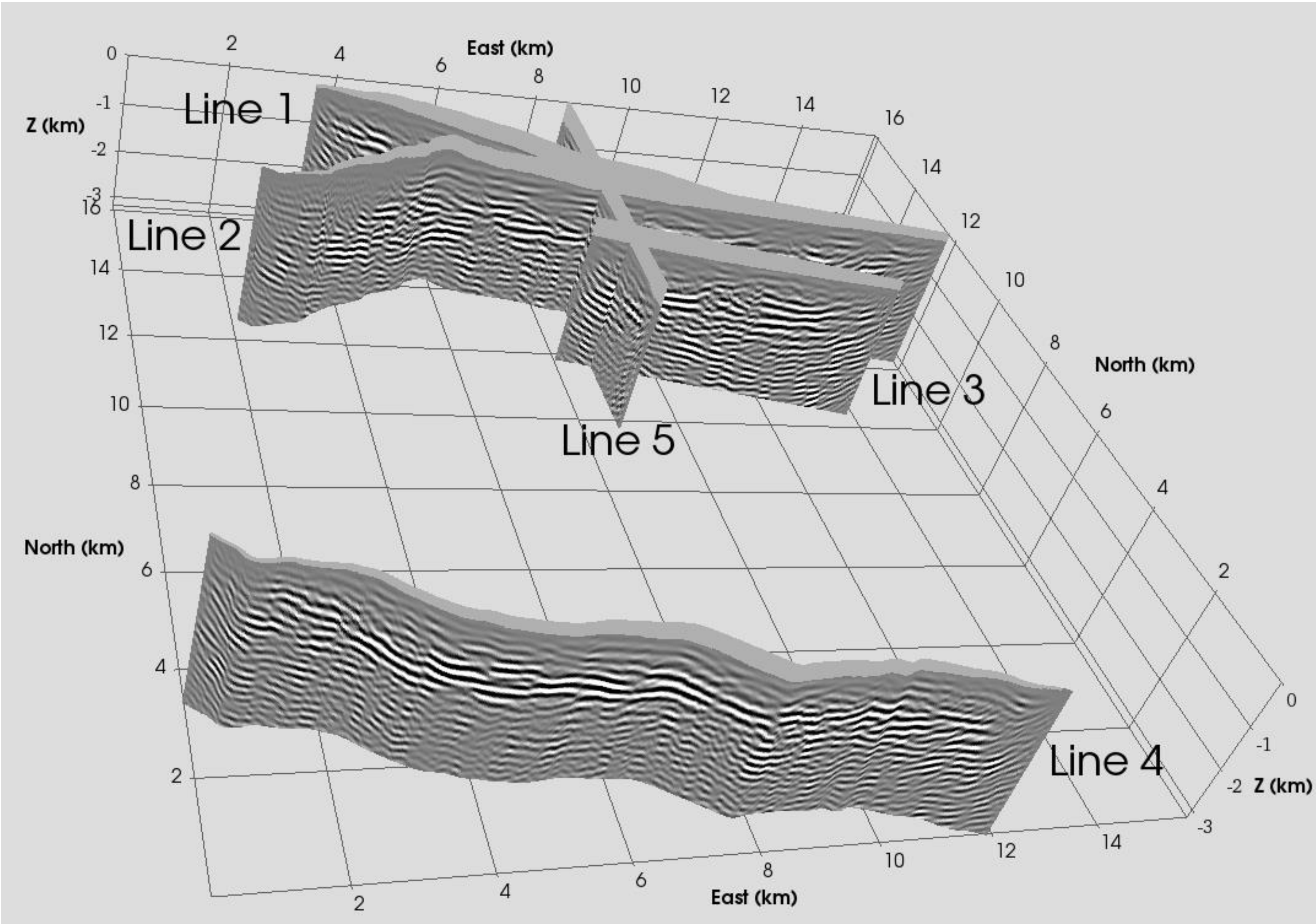
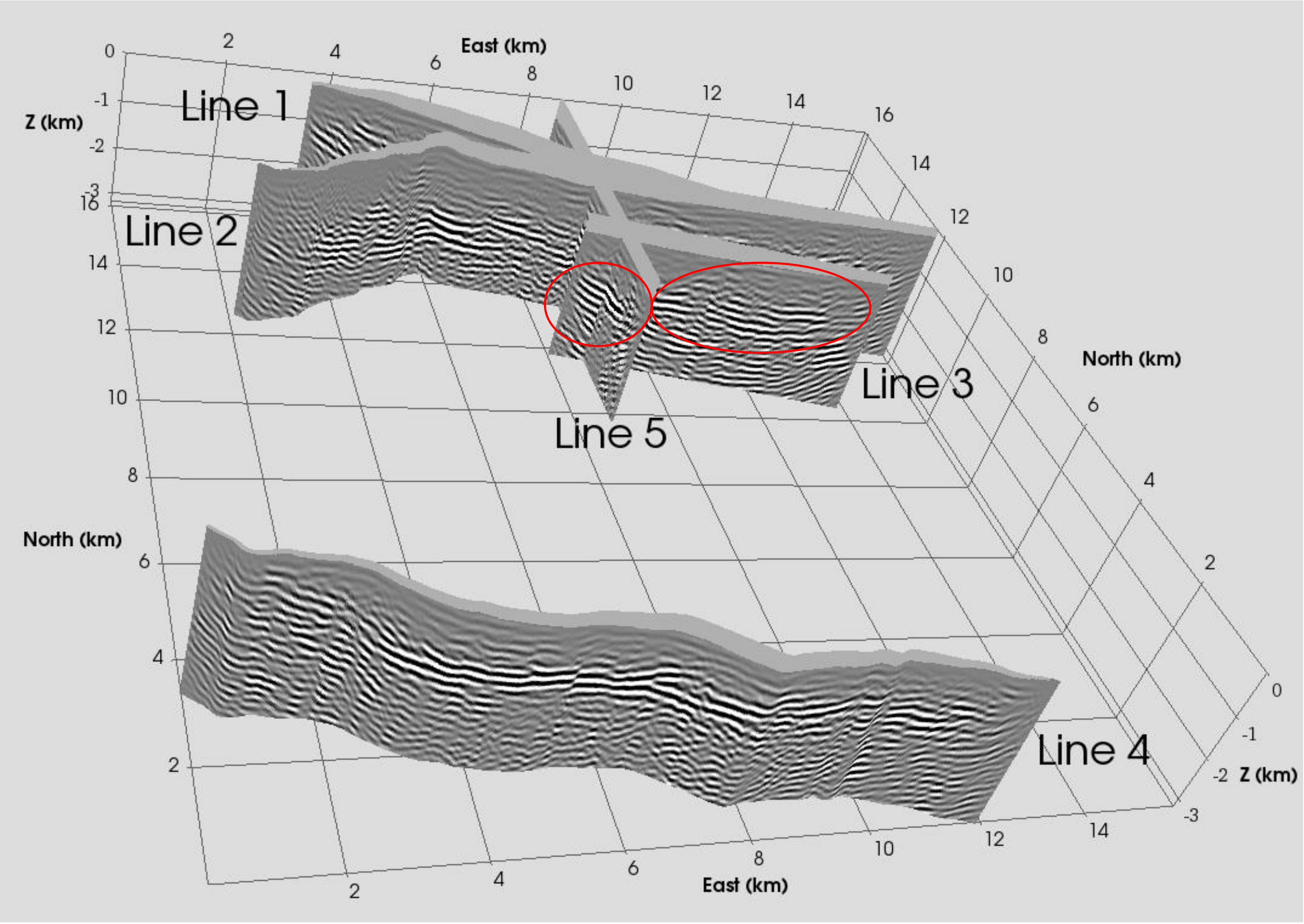


Image using inverted anisotropic parameters



Summary

- Our anisotropic reverse-time migration produces clear images of fracture zones with much fewer image artifacts than those obtained using isotropic reverse-time migration.

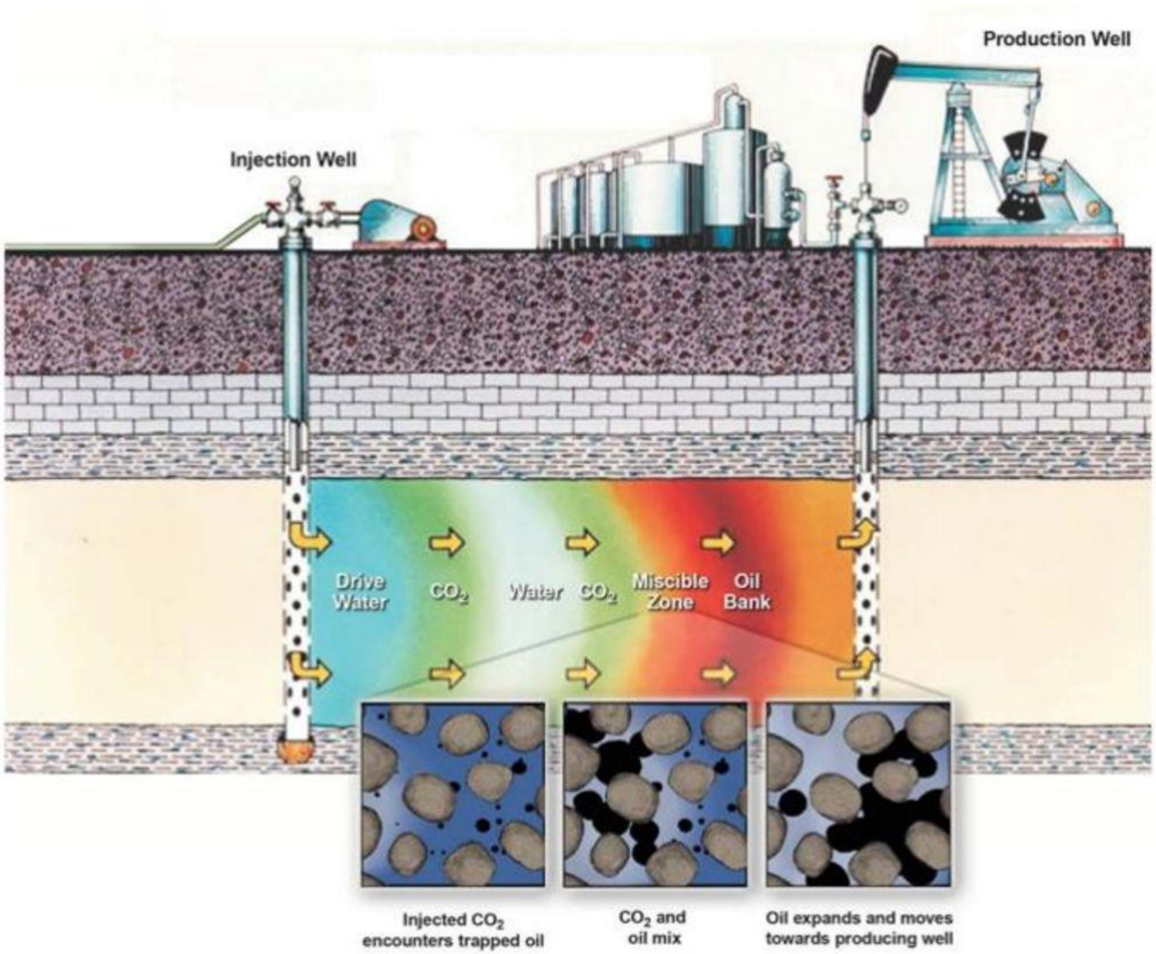
- We have applied our anisotropic acoustic reverse-time migration method to a 2D line of seismic data acquired at Eleven-Mile Canyon.

- Our results demonstrate that it is essential to properly account for anisotropic properties for fracture imaging.

Outline

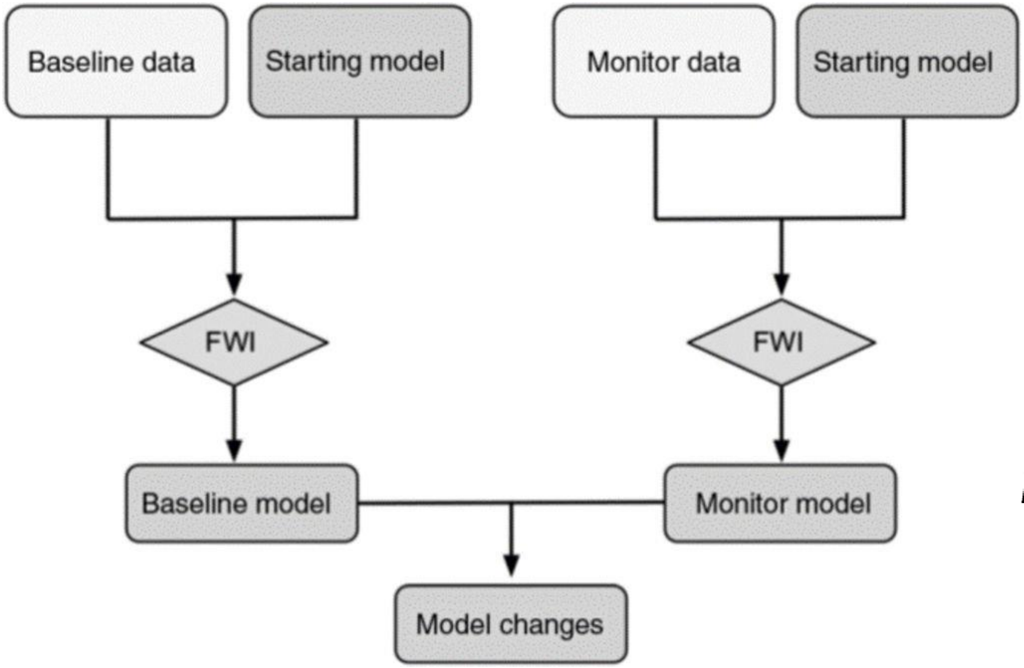
- Introduction
- Synthetic test
- Field data
- Monitoring CO_2 injection

CO_2 Enhanced Oil Recovery (EOR)



Reservoir

Conventional inversion for time-lapse seismic data

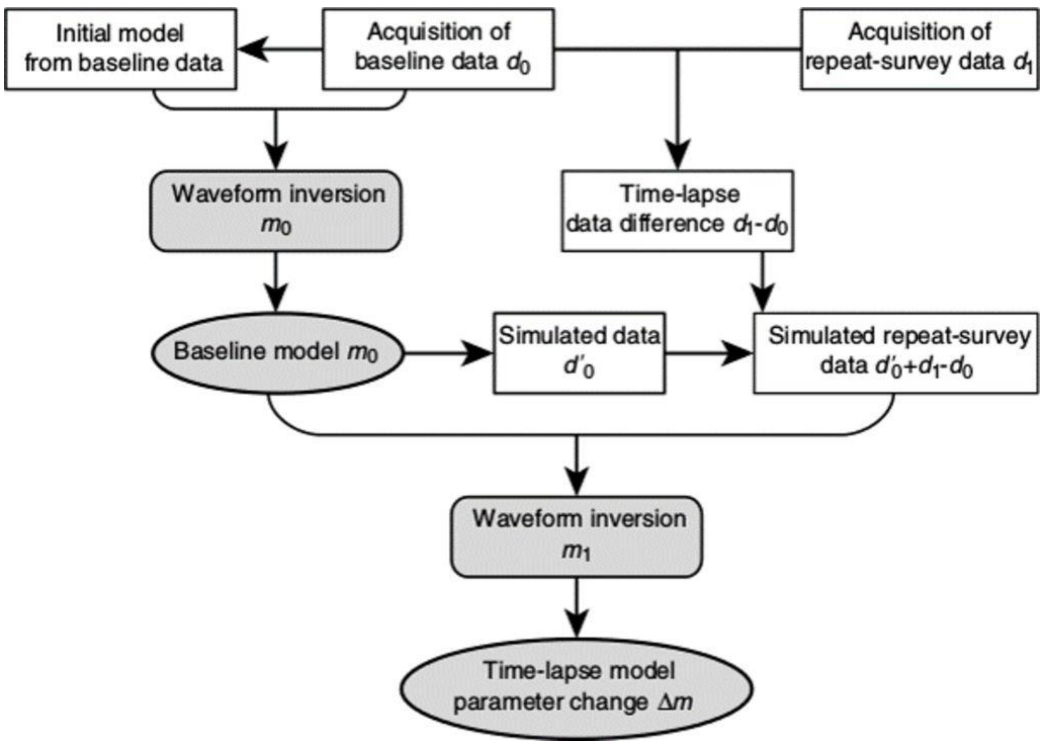


Full-waveform inversion

$$E = \sum_{(s,r)} \frac{1}{2} \int_0^T [\tilde{\mathbf{d}}(\mathbf{x}_r;\mathbf{x}_s) - \tilde{\mathbf{u}}(\mathbf{x}_r;\mathbf{x}_s)]^2 dt, \quad (1)$$

$$\mathbf{m}_{k+1} = \mathbf{m}_k + \alpha_k \gamma_k, \quad (2)$$

Double-difference waveform inversion for time-lapse seismic data



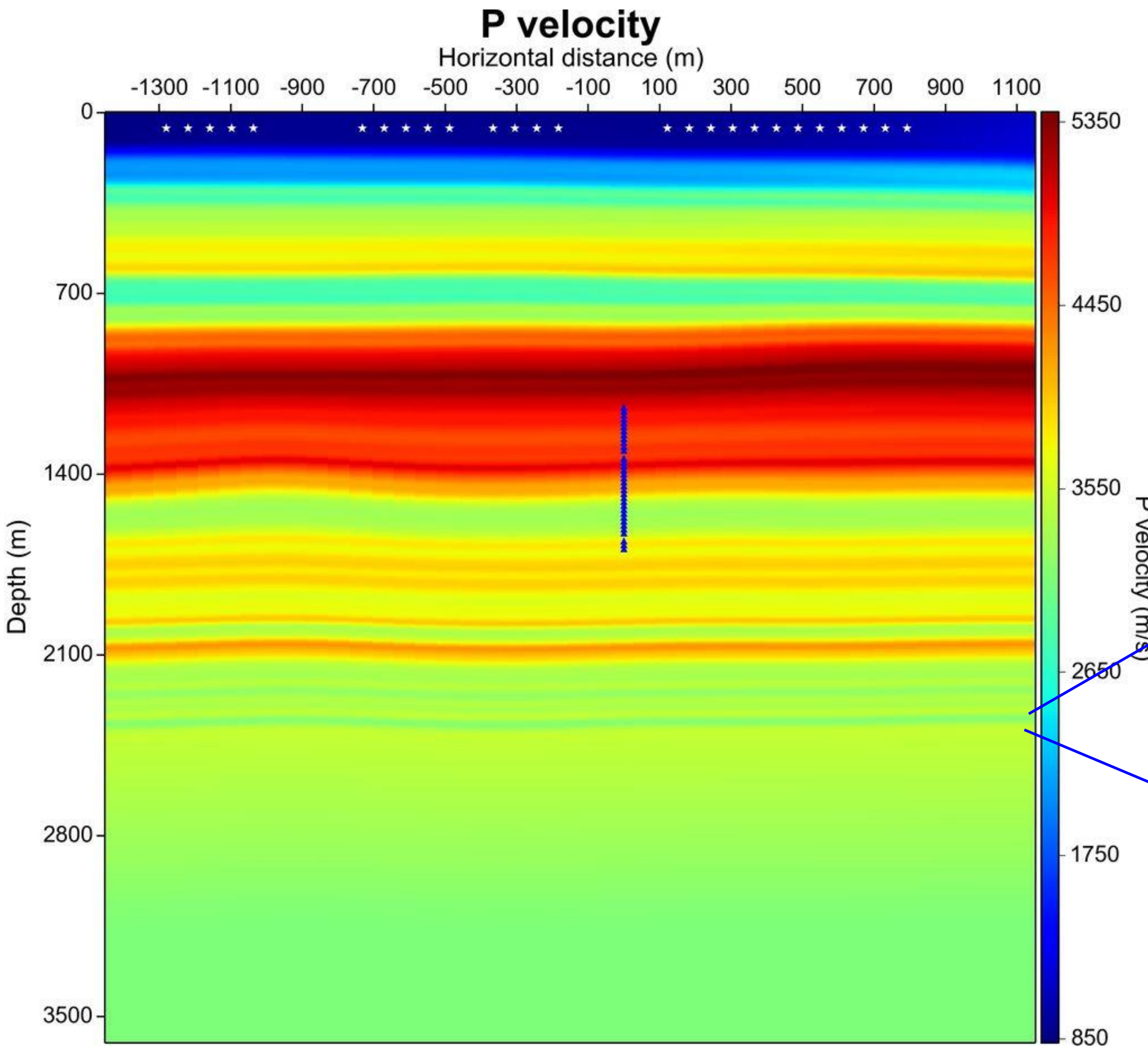
$$\overline{E} = \sum_{(s,r)} \frac{1}{2} \int_0^T [(d_1 - d_0) - (d_1' - d_0')]^2 dt.$$

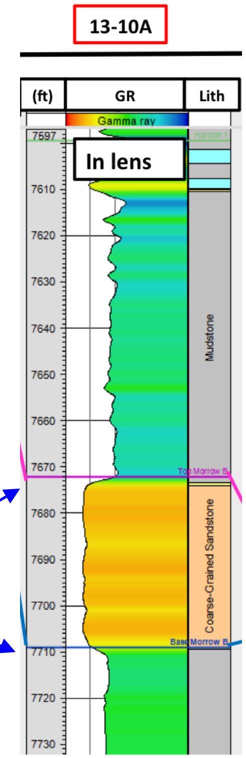
$$\delta\bar{d} = (d_1 - d_0) - (d_1' - d_0').$$

$$d(m_0^{\text{true}} + \Delta m^{\text{true}}) - d(m_0^{\text{true}}) = d(m_0 + \Delta m^{\text{true}}) - d(m_0).$$

$$m_0^{\text{true}} \approx m_0$$

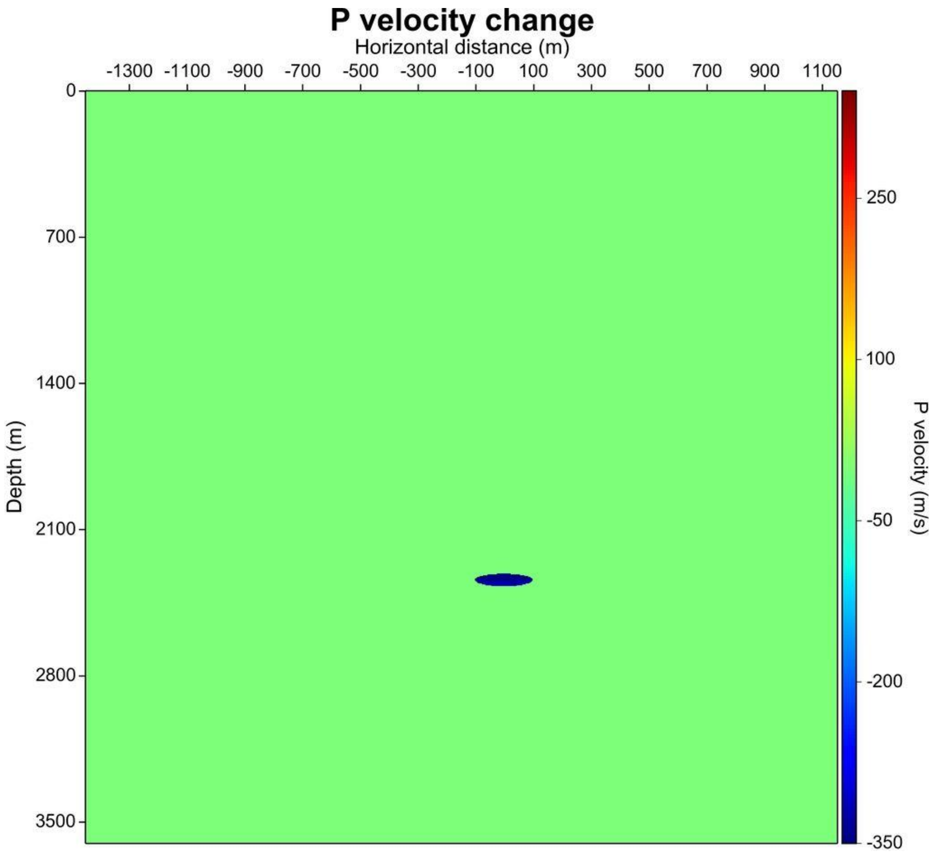
Denli and Huang, SEG, 2009;
Zhang and Huang, GJI, 2013





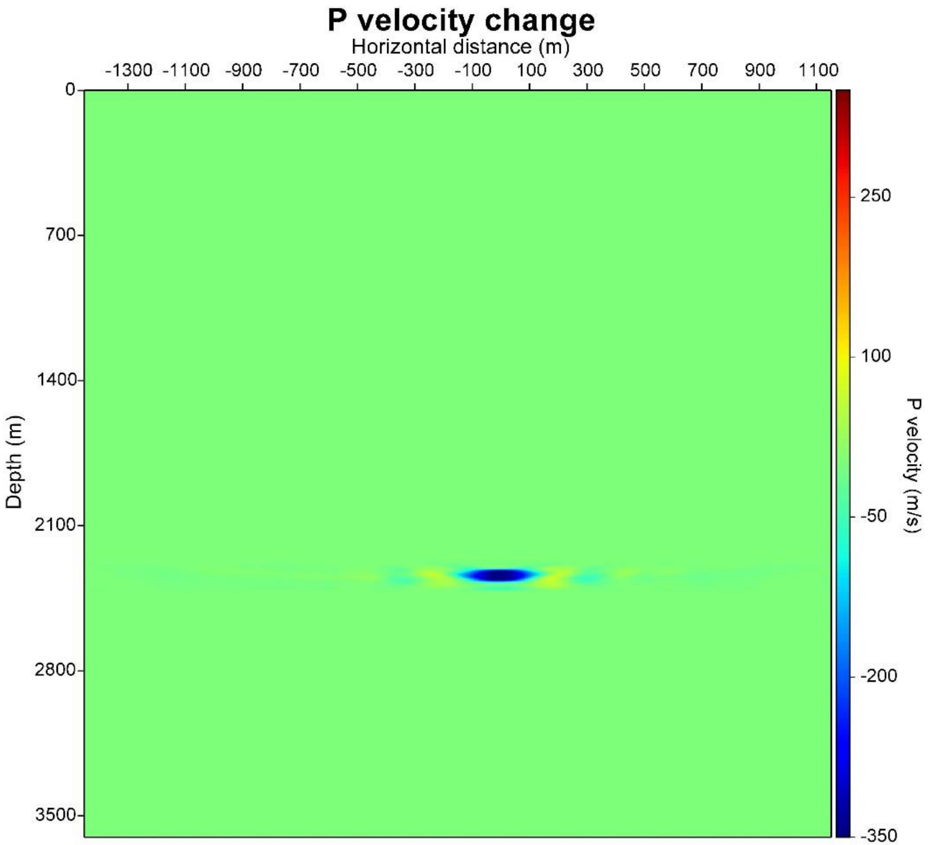
Target reservoir depth: 2.35 km
Morrow-B Sandstone Zone

Assumed P velocity change

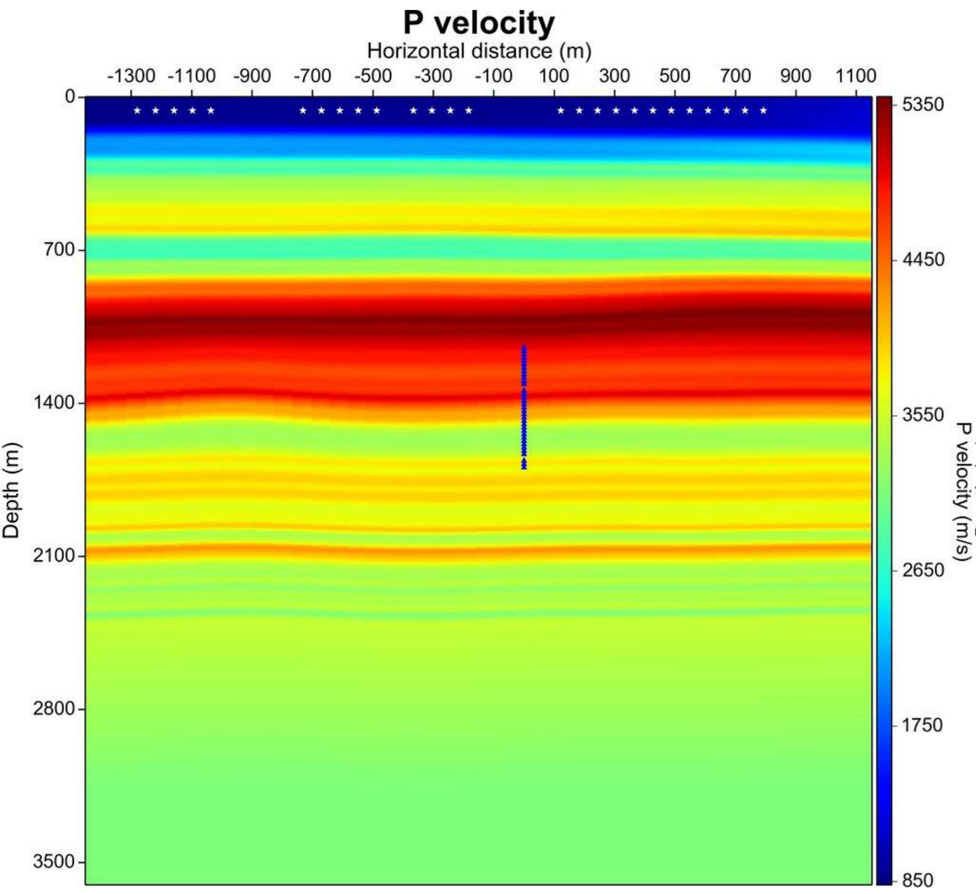


Assume that P velocity decreases 10%
within an ellipse (100m x 30 m)

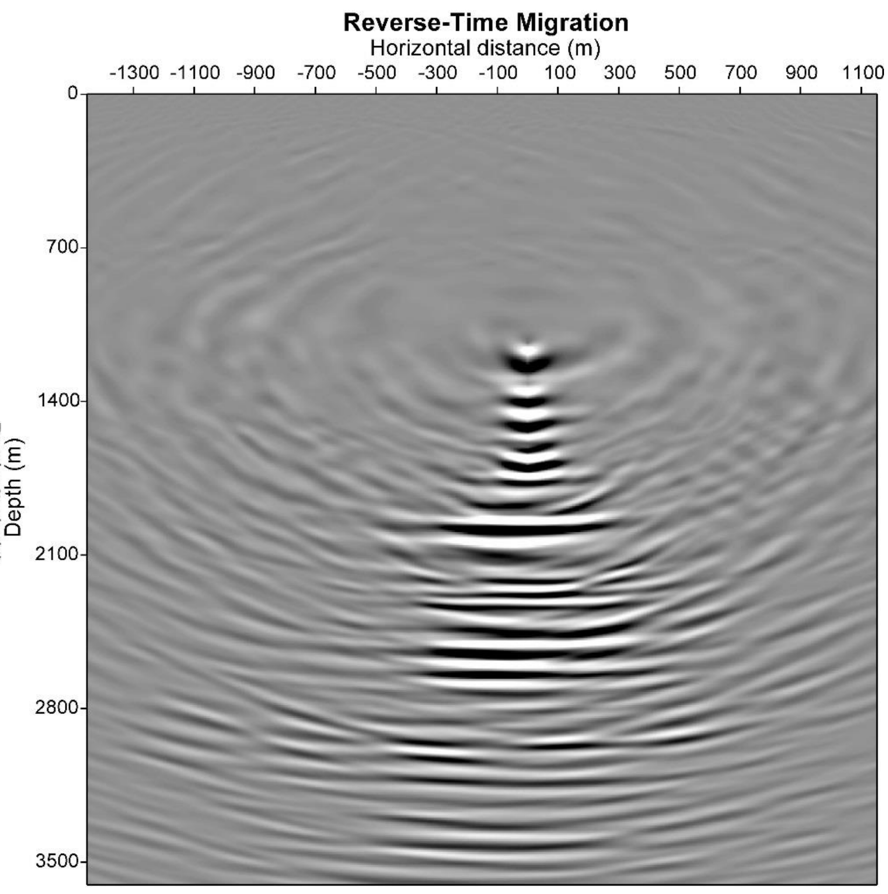
Recovered P velocity change



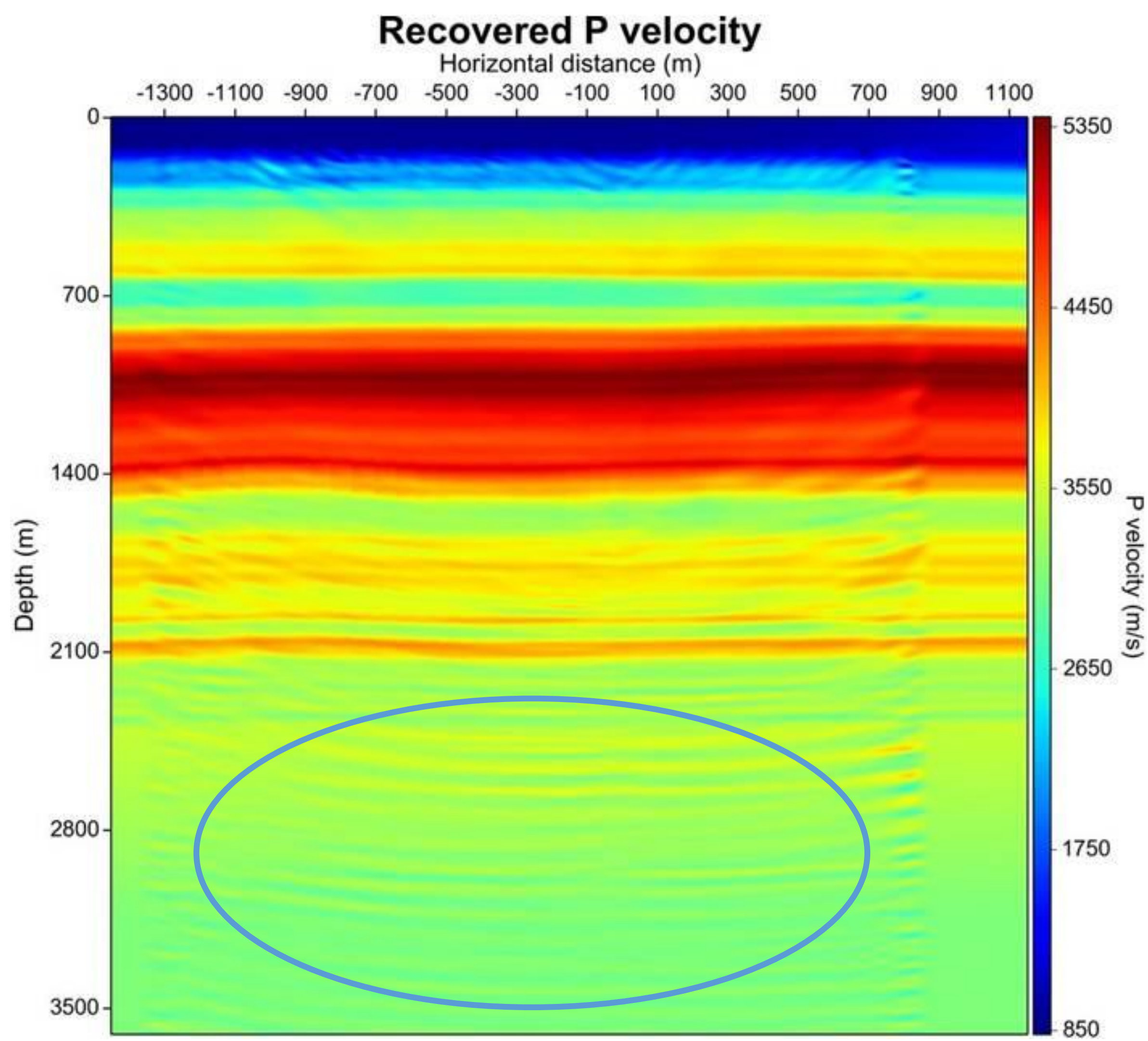
Backup



P velocity
Horizontal distance (m)
-1300 -1100 -900 -700 -500 -300 -100 100 300 500 700 900 1100
0
700
1400
2100
2800
3500
Depth (m)
5350
4450
3550
2650
1750
850
P velocity (m/s)

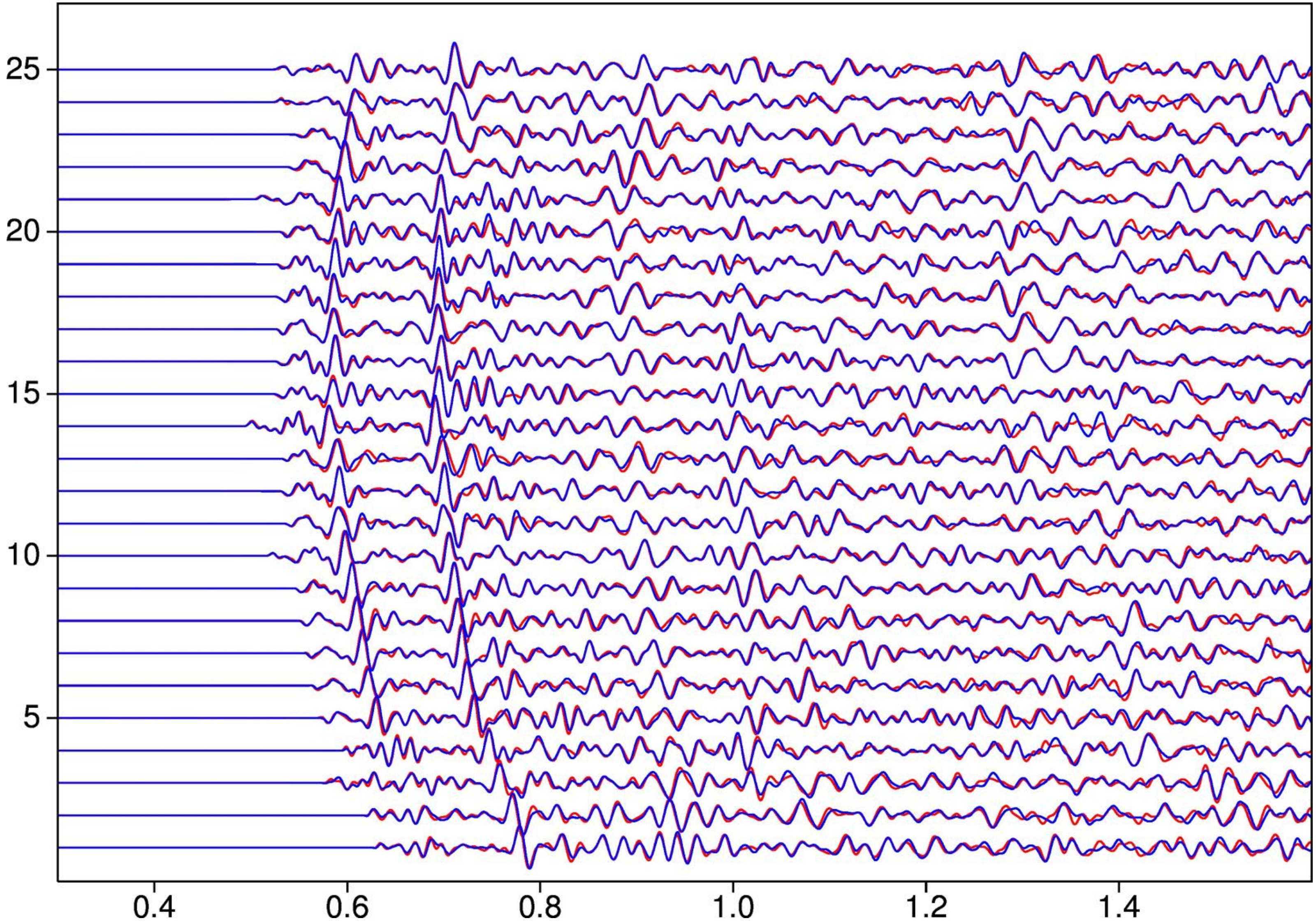


Reverse-Time Migration
Horizontal distance (m)
-1300 -1100 -900 -700 -500 -300 -100 100 300 500 700 900 1100
0
700
1400
2100
2800
3500
Depth (m)

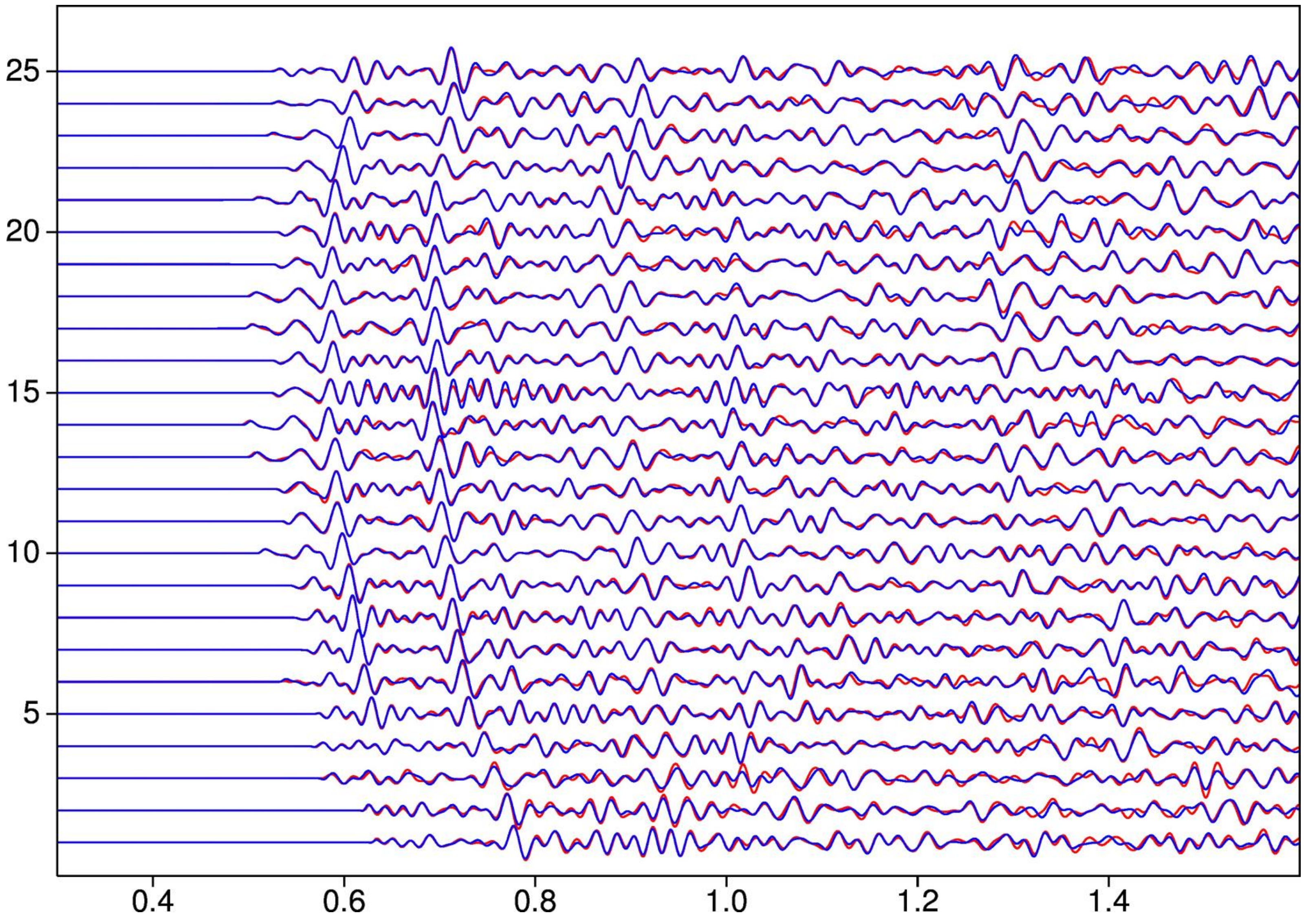


Recovered P velocity
Horizontal distance (m)
-1300
-1100
-900
-700
-500
-300
-100
100
300
500
700
900
1100
Depth (m)
0
700
1400
2100
2800
3500
P velocity (m/s)
5350
4450
3550
2650
1750
850

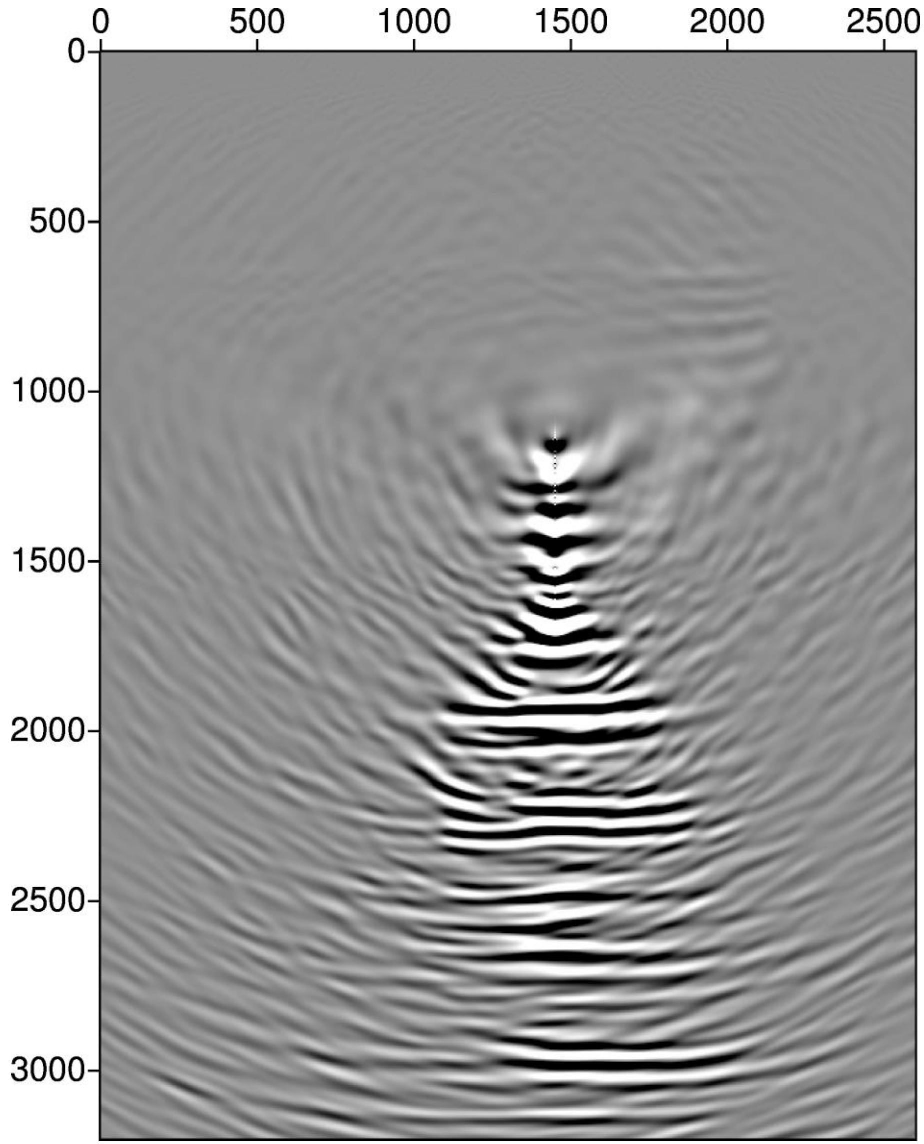
upP (one common receiver gather)



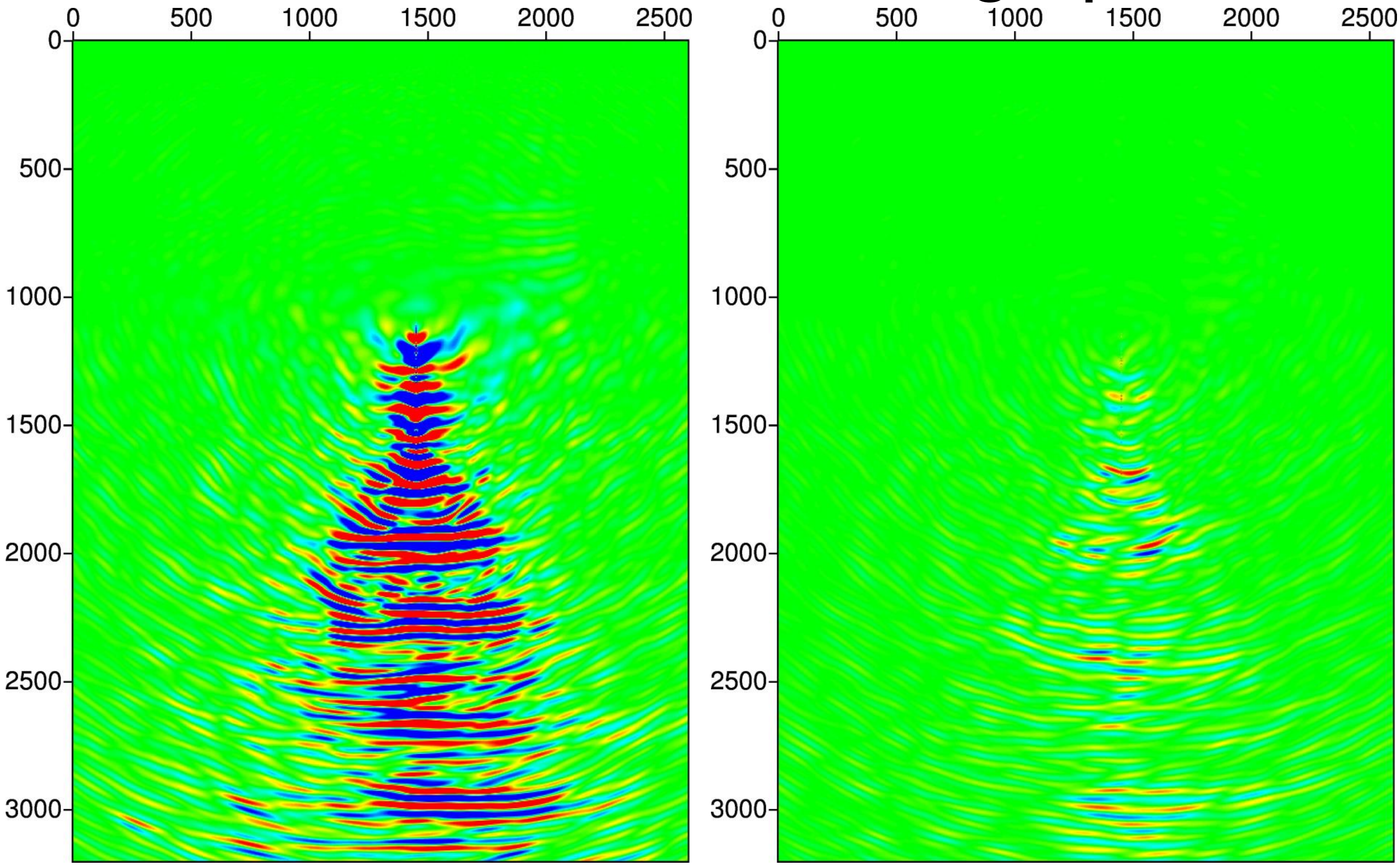
Balanced upP



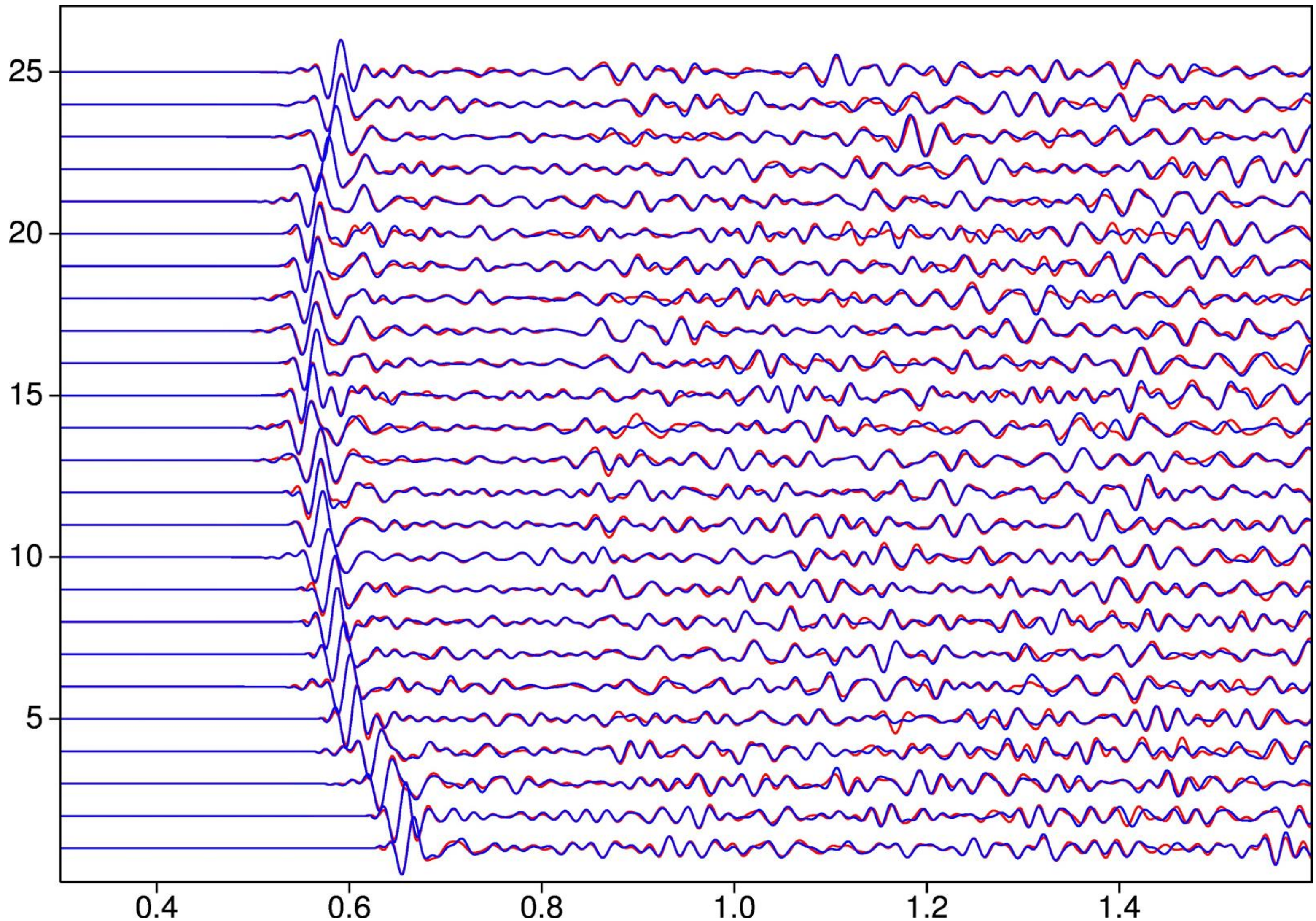
RTM using upP



RTM difference using upP



downP (one CRG)



P (one CSG)